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ELEMENTS

OF

PHYSICS. 2

BY [illegible]

C. F. PESCHEL,

14

PRINCIPAL OF THE ROYAL MILITARY COLLEGE AT DRESDEN,

ETC.

TRANSLATED FROM THE GERMAN,

WITH NOTES,

BY E. WEST.

Illustrated with Diagrams and Woodcuts.

PART II.

IMPONDERABLE BODIES.

I. — LIGHT, HEAT, AND MAGNETISM.

LONDON:
PRINTED FOR
LONGMAN, BROWN, GREEN, AND LONGMANS,
PATERNOSTER-ROW.
1846.

QC21
P47
v.2

TRANSLATOR'S PREFACE.

IN presenting to the English reader the Second Part of "Peschel's Elements of Physics," I may observe that it was with feelings of considerable satisfaction I received an intimation from my publishers that the sale of Part I. was so encouraging as to render it desirable that the work should be completed with as little delay as possible. It was gratifying to find that the estimate I had formed of the merits of my author was thus confirmed by the verdict of public opinion. The brief intervals of leisure which professional engagements have allowed me have been faithfully devoted to the preparation of these volumes.

I am bound to acknowledge the handsome treatment of the First Volume by the reviewers in general; and to the editors of the *Eclectic Review* and the *Civil Engineer and Architect's Journal* my thanks are especially due for their lengthened notices of it. The suggestion offered as to the reduction of ALL the measures to English standards has been attended to in the present Volumes. The different formulæ which occur in the Chapter on Heat have been adapted to Fahrenheit's scale; those calculated for the centigrade division are likewise retained for the convenience of any students who may have occasion to refer to foreign scientific works. Instead of a table of the tension of steam from 32° to 212°, calculated from Arzberger's formula, I have substituted one at page 223., Vol. II., presenting at a single view the results of Watt's, Dalton's, Ure's, and Southern's observations, together with the force according to a formula of Tredgold's; the tables which I have thus brought together are borrowed from that gentleman's work on the steam-engine.

Instead of detaining the reader with any remarks of my own as to the general plan of the work, I would call his attention to the extract given on the next page from M. Peschel's Preface.

I have added corrections of such errors in the first Volume as had escaped my notice at the time of its passing through the press; I have endeavoured to render the present Volumes as accurate as possible; how far I have been successful, it remains for the public to decide. Any suggestions that may be offered for the improvement of a second edition will be thankfully received.

AMERSHAM,
July 14. 1846.

EXTRACT

FROM

THE AUTHOR'S PREFACE.

"A MATTER of considerable difficulty in the preparation of a manual like the present is to determine the just proportions of the respective sections, chapters, and paragraphs, so that the subject shall be treated of in a manner neither too brief nor too diffuse. The purpose for which the treatise is intended will chiefly guide the author, who may yet, after all, be biassed to some extent by his individual views; for this reason a few remarks are added, explanatory of the course pursued.

"Among the Chapters that treat of the physical forces in general is one in which the leading phenomena of chemical attraction are explained. The varied relations in which Chemistry now stands to Natural Philosophy renders some acquaintance with its leading principles indispensable, or else many points in natural science, and especially what refers to Electricity, will be unintelligible. The chapter allotted to this subject is restricted to an explanation of the laws of affinity, the chemical division of substances into simple and compound, and chemical nomenclature and symbols; details as to the properties of particular substances are omitted, as belonging rather to a treatise on chemistry. The dynamics and statics of solid, liquid, and aëriform bodies are treated of in such a manner that a student may gain a theoretical knowledge of them without the aid of the higher mathematics. Crystallography occupies only a few pages, but the strength of materials, and the application of a solid's elasticity to measure force, are discussed at length. As the undulatory theory is constantly extending its domains in the physics of imponderable bodies, and is daily gaining new adherents, it is necessary to keep it in view in compiling a work on the natural sciences. The basis of this important theory is the doctrine of undulations, for the scientific development of which we are indebted to the MM. Weber. Professor Eisenlohr's services in this department are so great, and his views so comprehensive, that the chapter on this subject in his excellent "Lehrbuch der Physik," appeared to the author an unexceptionable model, and he has accordingly adopted the same systematic arrangement. In the section on acoustics, but a cursory notice has been taken of the theory of music, as being most in accordance with the character of this work.

"In the Second Volume the phenomena of the imponderable substances are explained, both according to the undulatory and corpuscular theories; in this portion of the treatise the phenomena attending the interference, the refraction, and polarisation of light, those of radiant heat, &c. &c., will be found to be handled at such length as the limits of the work allowed. The greatest difficulty was how to treat of Electricity, especially with reference to the theory of voltaic electricity, the range of electrical science having become so extended, and the decision of the scientific world being still suspended with regard to the different theoretical views which are held as the origin of voltaic electricity. The author felt that he must adopt one view or the other; and though he has decided in favour of the theory of contact, he has not omitted to adduce the strongest arguments by which the chemical theory is supported; and, in conclusion, he has presented the reader with the sketch of an intermediate theory. The last section treats of Electro-dynamics, the phenomena of

Electro-magnetism being first brought under review, and afterwards those of Magneto-electricity.

"A different arrangement of the type" [which has been adopted also in the translation] "distinguishes the paragraphs that contain the outline and general principles of the sciences from the supplementary matter, which enters more into detail; it is thought that this plan will be found convenient both for teaching and for self-instruction, as affording an opportunity of going more or less thoroughly into the subject, as may appear desirable.

"These supplementary observations contain also the mathematical demonstrations of the different doctrines, so far at least as they can be supplied by means of the elementary mathematics; experiments which may give the impress of truth to the theoretical paragraphs; brief notices of matters universally known or of minor importance; and fuller details of subjects less generally known, or with which it is desirable that the student should be well acquainted."

CORRIGENDA.

Vol. I.	p. 19.	line 14 from top,	for $-ab\,.\,ac\,.\,\cos.$	read	$-2ab\,.\,ac\,.\,\cos.$
	44.	17 -	*co. vers. sin.*	-	*vers. sin.*
	—	22 -	co. vers. sin.	-	vers. sin.
	54.	6 from bottom	$h : H$	-	$H : h$.
	111.	7 from top	$\frac{(mMV+mv)}{M+m}$	-	$\frac{m(MV-mv)}{M+m}$.
	112.	3 from bottom;	ninth	-	seventh.
	155.	7 from top	*the vessel*	-	*a cylindric or prismatic vessel.*
	162.	19 -	$\left(\frac{j^2}{J^2}C-J\right)$	-	$\frac{j^2}{J^2}(C-J)$.
	—	21 -	Do.	-	Do.
	165.	3 from bottom	2	-	½.
	—	2 -	$50 \cdot 70 = 3500$	-	$50 \cdot 72 = 3600$.
	229.	3 -	hydrogen	-	aqueous vapour.
	230.	8 from top	Do.	-	Do.
	235.	5 -	B—(log. β', &c.	-	β—(log. β', &c.
	240.	14 from bottom	$l = -12 \cdot 3$	-	$t = -12 \cdot 3$.
Vol. III.	p. 12.	17 from top	ἐλεκτρον	-	ἠλεκτρον.
	78.	4 from bottom	electrometers	-	electromotors.

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ELEMENTS

OF THE

PHYSICS OF IMPONDERABLE BODIES.

IMPONDERABLE SUBSTANCES, OR ETHEREAL POWERS IN GENERAL.

§ 270.

The phenomena of *Light*, *Heat*, *Electricity*, and *Magnetism* are so peculiar in their nature that we cannot assume that they result from those general and fundamental properties of matter which have been treated of in the former volume of this work.

The distinguishing characteristic of these substances (if such they be) is, that they are not permanently resident in those bodies in which their presence is observed: they also affect our senses peculiarly; thus, light excites no organs but those of vision, heat acts only on our feeling; electricity, on the contrary, influences all our senses, whilst magnetism exerts upon our frames no perceptible influence whatever. Light appears to be diffused throughout the universe, but heat, electricity and magnetism, have not as yet been proved to exist beyond the limits of our globe; it is, however, highly probable that their range is as wide as that of light.

§ 271.

The generally prevailing theories by which it is proposed to explain the various phenomena of the imponderable substances are two.

Some philosophers assume for this purpose the existence of a peculiar class of substances differing from all the other forms of matter in this, that they are not subject to the laws of gravity, and that they are consequently destitute of weight, whence the term *Imponderable Substances*; they further suppose them to be of so subtile a nature as to pass through all other material bodies, by which, therefore, they cannot be either inclosed or divided.

According to the other hypothesis, a certain imponderable, highly elastic fluid, styled the *ether*, is supposed to fill all space throughout the universe, and to occupy the vacancies between the atoms of bodies: on this fluid different forces are conceived to act, so as to produce the effects known to us as light, heat, *etc.*

§ 272.

These ethereal forces, whose nature is involved in great obscurity, possess one remarkable property, called *Polarity*, which is most perfectly developed in electricity and magnetism. Polarity consists in the tendency shown by two contrary *polar forces* to become united, and in the efforts of each polar force to excite its opposite in other bodies, whence similar polar forces invariably repel each other. When these opposite forces effect such a union as mutually to destroy each other's energies, all their external operations cease, and the forces are said to be *neutralised* and the condition thus obtained is one of equilibrium or rest. Polar energy displays itself in a disturbance of the polar forces by external causes, and this disturbance continues until a perfect neutralisation is re-established. When the forces are in this state of activity a body is said to be *polarised*, and the points at which their energy is most strongly marked are denominated *poles*. The signs + and —, which represent opposite values in mathematics, have been adopted as the symbols of these forces; whence the law of polarity may be thus expressed; + and — polarity represent attraction, + and + or — and — repulsion, and equal + and — give 0, *i.e.* neutralisation, equilibrium, or rest.

From the rapid advances recently made in this department of natural science, and from the analogies which present themselves between light and heat, electricity and magnetism, we are led to the conclusion that, probably, the phenomena of these four ethereal forces are, after all, but modifications of a higher principle with which we are not yet acquainted; a principle that, perhaps, plays an important part in the obscure operations of that vitality which animates all organised beings.

PART I.

LIGHT, HEAT, MAGNETISM.

SECTION I.

LIGHT.

I. OF LIGHT IN GENERAL.

§ 273.

Light renders all external objects visible; the organ through the medium of which we become acquainted with the universe around us is the eye, as the action of light upon it immediately affects the optic nerve. Light has also the property of *communicating heat* and producing certain *chemical*, *electrical*, and *magnetic* (?) *effects*, so that it exercises an important influence on all organised bodies.

In the following chapters those phenomena which are caused by the first-named property of light will be described and explained, and such as result from the other properties we have mentioned will be noticed at the close of this section, and in the sections on Heat, Electricity, and Magnetism.

§ 274.

To give a complete explanation of the various phenomena of light, it would be requisite for us to have an accurate knowledge of its nature: since we do not possess this, recourse has been had to theories, two of which are the most generally received, viz., the *Emanation* or *Corpuscular Theory*, and the *Undulatory Theory*.

According to the former of these hypotheses, light is an imponderable substance, whose inconceivably minute particles produce the sensation of sight by their action on the eye, in a manner analogous to that in which the fine particles of any odorous substance excite the sense of smell. The atoms of light are further supposed to be subject to the attractive and repulsive forces of the bodies on whose surfaces they fall, and with regard to these forces to display different degrees of inertia.

Newton originally constructed this hypothesis, which has been still further developed by *Biot* and *Laplace*.

According to the *Undulatory Theory*, light is occasioned by the ether, which is supposed to be diffused throughout space (§ 271.); this subtile and elastic fluid, whose density and elasticity are not uniform or unchangeable, is capable of receiving and transmitting undulatory movements; it is further assumed that when a certain velocity has been attained, the waves of ether, impinging on our eyes, excite the emotion of sight, just as the waves of air excite that of hearing. To explain most of the phenomena of light, reference may be made to others of sound, which exactly resemble them.

This hypothesis was originally founded by *Descartes*, *Huygens*, and *Euler*; and in later times it has been adopted and enlarged by *Young*, *Fresnel*, *Frauenhofer*, *Herschel*, and other philosophers.

The greater number of phenomena may be equally well explained by either theory, yet it must be admitted that some of the more recently discovered properties of light are more satisfactorily accounted for by the second hypothesis, for which reason it now numbers most adherents.

§ 275.

With respect to the production of light, bodies are divided into *luminous* and *non-luminous*.

Luminous bodies are those different sources whence light emanates, and which are thus visible of themselves. The greatest permanently luminous body is the *sun*: the *fixed stars* resemble him but in the effects they produce, so far as we are concerned, they are vastly inferior. *Bodies in a state of combustion*, whose efficacy is, however, but transient, are extremely serviceable as sources of light.

According to the corpuscular theory, light issues in an uninterrupted stream from the luminous body; according to the undulatory theory the surface of such a body is set in a state of vibration, and the tremor is communicated to the surrounding ether, resembling in this a sonorous body.

The various luminous bodies which serve as the sources of light may be classed pretty much as follows:—

1°) All those heavenly bodies which shine by their own light; of these, as has been remarked already, the sun is the chief.

2°) *Chemical light*, or that which is obtained by combustion.

3°) *Electric Light*, which under various modifications accompanies the development of electricity; this will be treated of more fully in the section on Electricity.

4°) *Light by Friction*, which is obtained by rubbing together, or striking either similar or dissimilar bodies, (not, however, all bodies without exception,) either *in vacuo*, or in gases, which are not supporters of combustion, or even, according to *Heinrich*, under water and oil; this species of light seems to be of an electrical nature, unless, indeed, it is merely the luminous appearance of the fragments detached from combustible bodies. Similar appearances may be observed in splitting or rending some solid bodies, especially crystals, as well as in the sudden condensation and expansion of gases, and in the sudden and violent compression of liquids.

Phosphorescent Light is that which is emitted by many bodies at a low temperature, and is unaccompanied by any essential alteration in their properties; it is so feeble as to be scarcely perceptible except in the dark The luminous appearance of common phosphorus is the result of chemical action, for it obtains only when this substance is in combination with oxygen or chlorine. Of this light there are three kinds:

5) *Phosphorescence by insulation* is a property possessed by *O*
many bodies, in consequence of which, after long exposure to the sun's rays, they become luminous in the dark. Wall first discovered this property in the diamond; but it has been subsequently found to exist in several other minerals, especially in certain varieties of fluor-spar. There are also several chemical compounds, as the Bologna Stone and others, which retain for several hours the luminous property they acquire by being insulated. It does not cease even C
when the phosphorus is immersed in water, or in gases which are not supporters of combustion. These bodies become luminous in the dark, on the application of heat to them. The cause of this phosphorescence is not yet known with any considerable degree of accuracy.

6) *The Phosphorescence of organic remains in a state of decomposition.* The luminous appearance of touch-wood is, perhaps, the most generally known illustration of this property in decayed vegetable matter; the same phenomenon may be observed in animal matter, especially in sea-fish, on which a luminous film is formed. In all these cases phosphorescence seems to be owing to a low sort of combustion, as the emission of light decreases on rarefying the air.

7) *Phosphorescence of organic bodies during life.* The plants which display this light the most conspicuously are the marigold and the yellow lily, a little after sunset, when the atmosphere has been very much heated in July and August; probably it is of an electrical nature. The phosphorescence of many animals, that of most of the infusoria, by which the sea acquires a luminous appearance frequently to a considerable distance, that of many species of zoophytes, mollusca, crustacea, and insects, especially that of the fireflies, scolopendræ, and glow-worms, remains problematical.

In vacuo, and in all non-respirable gases, it becomes extinct; in oxygen gas it shines with increased brilliancy.

Non-luminous bodies are such as become visible only when light falls upon them from some luminous body.

According to the emanation theory, non-luminous bodies become visible in consequence of their reflecting the particles of light which impinge on them; according to the other hypothesis, the waves of ether recoil from the surfaces of these bodies, just as the waves of sound rebound and form an echo. (§ 206.)

The heavenly bodies which shine only by reflected light are the planets, their satellites, and probably, in some degree, the comets also.

§ 276.

Bodies, considered as to their capacity for transmitting light through their substance, are divided into *transparent* and *opaque*.

Transparent or *diaphanous bodies* are such as give a free passage to light through the matter of which they are composed, or, in other words, they are such as admit of our seeing other bodies through them with a greater or less degree of distinctness; as instances we may mention the atmosphere, water, and glass.

A perfectly transparent body does not exist, for such a body would allow all the light which falls on it to pass through, and as it reflected none it would itself be invisible. The greater the quantity of light a body transmits and the smaller the portion reflected, the nearer it approaches to perfect transparency. The following experiment will shew this, as to one of this class of bodies.

First Exp. Admit a ray of light into a darkened room, and let it fall upon the surface of some water contained in a glass vessel with parallel sides. The ray will pass through the water, but some portion of the light will be evidently reflected from its surface. The same will be observed if for water we substitute a thick plate of glass.

There are many degrees between perfect transparency and absolute opacity, for each of which gradations distinct appellations do not exist; bodies, however, which occupy a mean position between these extremes are said to be *translucent*. They permit the passage of so small a portion of light, that other bodies cannot be seen at all through them, or if seen, but imperfectly; such are foggy air, paper saturated with oil, laminæ of horn, &c.

Some of the most transparent bodies are, the atmosphere on a clear day, a few of the other gases and vapours at a high degree of expansion; most liquids and many solids also are more or less transparent. This property depends, not merely on the absolute transparency of a body, but also on the density of the medium through which the light passes. The thicker any substance is, the less is its transparency. A very thin plate of crown glass would seem to be perfectly transparent, but if several such plates were to be piled one on the other, their transparency would be found to diminish as the number of plates was increased. For a similar reason, distant objects being viewed through a large extent of the atmosphere, are less distinct than those which are near to us. No exact connection has yet been established as existing between the transparency of a body and the material of which it consists. The regularity of its internal structure (§ 88.) and the polish of its surface exert a considerable influence on the capacity of a body for transmitting light; on this account colourless crystals are highly transparent. A remarkable proof of the correctness of the above remarks is furnished by the diamond and common charcoal, as also by the fact that many bodies acquire the property under consideration, if their pores be filled with either oil or water.

Second Exp. Ground glass is not transparent, but by pouring oil of turpentine, or indeed any other oil upon it, it is rendered transparent, or at least translucent in a much higher degree. — *Hydrophane.*

Third Exp. Two plates of ground glass may be rendered transparent by pouring a little oil of turpentine between the surfaces in contact.

Opaque bodies are all such as obstruct the passage of light, and through which consequently objects are not visible.

It is probable that no body whatever is absolutely opaque, if it be reduced to laminæ of sufficient tenuity, since light is found to pass readily through leaves of gold and other metals.

Fourth Exp. If a pane of glass be covered on one side with leaf-gold, objects will be seen through it, and a greenish tinge will be imparted to them.

According to the corpuscular theory, transparent bodies allow a passage more or less free through their substance to the particles of light, and opaque bodies are supposed to be such as light cannot penetrate. According to the undulatory theory, it is assumed that transparent bodies possess the property of transmitting the luminous vibrations of the ether in the same manner as the vibrations of the atmosphere are imparted to solid bodies; the particles of ether that occupy the spaces between the atoms of the transparent bodies being put into a state of vibration. The degree of a body's transparency is further supposed to depend on the intensity with which this vibratory motion is transmitted on the opposite side of the body. Bodies which are perfectly opaque will by this theory be such as altogether destroy the luminous vibrations of the ether.

II. THE PROPAGATION OF LIGHT; OPTICS.

§ 277.

Light is propagated in *right lines* from every luminous point in a homogeneous transparent medium, and every such right line proceeding from a luminous point is called a *ray of light.* The following experiments will serve to shew that light is thus propagated:—

First Exp. Interpose any opaque object between your eye and the flame of a candle, and the latter will cease to be visible to you.

Second Exp. Admit the sun's rays into a darkened room through one or two apertures; the light will appear in the form of straight lines or rays.

Since a luminous point is visible in all directions, we infer that *light is propagated in every direction in divergent rays;* in other words, by *radiation.*

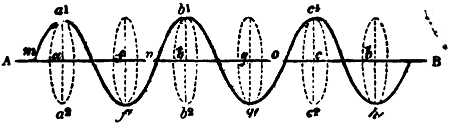
According to the corpuscular theory, light is projected eccentrically from every luminous point, like the radii produced of a sphere, and the term "ray of light" is used to express the direction in which an atom, or a succession of atoms, of this matter, is supposed to move.

According to the undulatory hypothesis, the propagation of light proceeds from every luminous point in all directions, conformably to the laws of undulatory motion. (§ 226.) Every line that can be imagined to be drawn perpendicularly to the surface of a wave of light constitutes a ray, and if such a line be produced until it is terminated in the luminous point, it will give the direction in which the undulations are propagated.

The following explanatory remarks will perhaps render the above condensed account of the undulatory theory, as far as regards the propagation of light, more easy to be understood; they will also serve to shew more plainly the positions occupied by the different particles of ether.

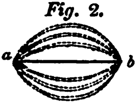
Let us suppose, first, that light is propagated from a luminous body only in the direction of A B, *Fig.* 1; then

Fig. 1.



all the particles of ether lying in this path will be put into a state of vibration, the directions in which they move being perpendicular to A B. Let *Fig.* 2 represent a perspective view of the portion *a b* of the ray. This motion of the ether will consequently generate a progressive undulation (§ 212.); the curve *fig.* 1 will represent the situations of the different atoms of ether at any particular moment of their undulation. In the line A B the particle *a* would vibrate constantly in the circle a^1 a^2; on arriving at a^1 its velocity would be *nil*; but as it returned to its original position its velocity increases, until, on reaching *a*, it will have acquired its maximum. In consequence of its inertia, the particle will still move with retarded velocity to a^2, at which point its velocity will once more be *nil*; when it will commence its return under circumstances exactly similar to those already described. This vibratory movement of the first particle is not imparted instantaneously, but successively to the other atoms in the direction of the ray. Supposing that all the atoms of ether in the line A B were in a state of repose when *a* began to vibrate, then they would all acquire a similar movement in succession as they were ranged from A to B. Thus, whilst *a* performs one complete oscillation from a^1 to a^2, and back again to a^1, the motion would be imparted to the next atom, *b*, which would begin its first vibration at the very moment that *a* was beginning its second; from that point of time, therefore, *a* and *b* would perform similar vibrations, *i. e.* they would make their excursions in the same directions simultaneously, they would return to their original points, *a* and *b*, together, and would together arrive at their greatest distance from A B. Reasoning in like manner, we may further assume that the particle *c* will commence its first vibration when *b* is beginning its second, and *a* its third, and that from that moment *c* will make corresponding vibrations with *a* and *b*; these consequences may be inferred to apply to all the atoms as far as B, where the ray was supposed to end.

Fig. 2.



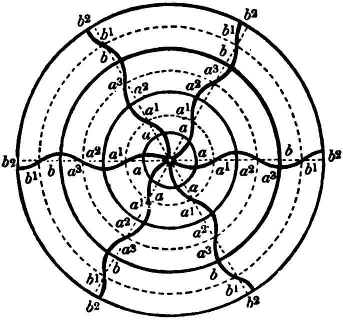
Now, when all the atoms of ether composing the line A B have acquired this oscillating movement, the equal distances

a' b', or *mn no*, will constitute a *complete wave.* All the particles of ether lying exactly between these first-named points, *viz. f, g, h*, which are just *half a wave* from the former, are in an opposite state of vibration, so that when *a, b, c, etc.* attain their greatest distance, a', b', c', above A B, *f, g, h*, will be as far below it at the points f', g', h'; all the particles, however, arrive simultaneously at their points of repose, *a, b, c*, and *f, g, h*; only it must be borne in mind that they pass each other in opposite directions.

From these considerations, it follows that all the particles of ether in the direction of a ray of light, which are at the distance of 1, 2, 3, 4 . . . *n* waves apart, vibrate with equal velocities in the same direction, but that all which are ½, 1½, 2½, 3½ . . . *n* + ½, waves apart, move with equal but opposite velocities.

If, now, we further suppose that light is propagated from a luminous point in a plane in all directions, with equal force and velocity, it is clear that we shall have a system of circular waves, resembling that which obtains in non-elastic fluids (§ 216). *Fig.* 3 will be a tolerably accurate representation of such a system. The particles of ether in all the rays which proceed from the luminous point A and at equal distances from A will be in the same state of vibration, as has been already shewn in *Fig.* 1, and as is now represented in the circular waves *a a a* . . . a^1 a^1 a^1 . . . a^2 a^2 a^2 a^3 a^3 a^3 . . . *b b b* . . . b^1 b^1 b^1 . . . b^2 b^2 b^2 . . . &c.

Fig. 3.

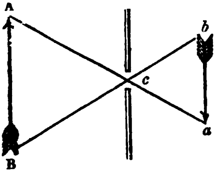


But it has been already stated that light is propagated in *all* directions; in order, therefore, to obtain an accurate idea of the radiation of light, we must conceive the circular waves *Fig.* 3 to revolve about one of their diameters as an axis, so as to generate spherical waves, in which all the atoms of ether vibrate equally.

§ 278.

The *Camera Obscura* (an invention of Porta's, in the middle of the 16th century) acts on the principle that light is propagated in right lines. This instrument consists of a darkened chamber, into which the rays of light, from an illuminated object, are admitted by means of a small aperture; these rays are received upon a white screen, and thus every point of the object forms a figure coloured with its appropriate tint, the figure being of the same shape as the aperture. These figures, combined, form an inverted image of the object.

Fig. 4.



Let A B *Fig.* 4 be the object from which the rays pass through the aperture *c* into the darkened chamber, and are received on a vertical wall; the ray of light A *c*, which descends from the head of the arrow, will produce the image of the head at *a*; whilst the ray B *c* from B ascends through *c* and depicts the feather at the top of the image. In like manner, the rays from all the intermediate points between A and B pass through *c* and impinge upon the wall at different points between *a* and *b*, so as to form altogether the line *a b*, which is necessarily an inverted image of A B.

Exp. Darken a room completely, and make a small hole in the window-shutter, so as to admit the light from external objects, and they will be depicted on the wall opposite to the opening; it will be better still if a white screen be placed at some distance from the wall, as the objects will in that case retain their natural colours; on whichever surface the images are received they will necessarily be inverted. The smaller the opening the more clearly will the outline of the object be defined; the light will, however, be proportionably lessened. As the size of the aperture is enlarged the brightness of the picture will be increased, but the distinctness of its outline will be diminished in the same ratio; and, lastly, the proportions of the image are increased the greater its distance from the aperture which admits the light. All these modifications are easily explicable from what has been already said with regard to the formation of these images in the § above.

§ 279.

If an opaque body be enlightened on one side only, the side which is more remote from the source of light will continue dark, and beyond it there will be a space not affected by the light; this constitutes the *shadow* of the opaque body: if any object intercept this space, that side of it which is next to the opaque body will be darkened by the projection of the shadow upon it.

If the light proceeded from a single point we should obtain the boundary line of a body's shadow by drawing right lines from this luminous point to every point in the boundary lines of the body's figure and then producing them. The lines thus drawn from the luminous point to the object would be divergent rays, and the space they contain on the farther side of the body would be its shadow.

If the object have a curved boundary the shadow will be a truncated cone, *fig.* 5.; if its boundary be rectilinear, the shadow will be a truncated pyramid, *fig.* 6.

Fig. 5.

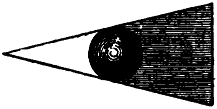
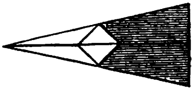
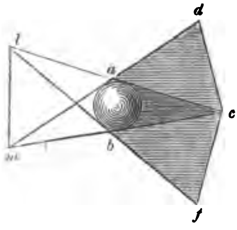


Fig. 6.



If the luminous body, as in fact is always the case, consists not of one but of many luminous points, then the space behind the opaque object will contain two shadows, *viz.* the *umbra*, which is perfectly dark, and the *penumbra*, which is partially illuminated, and which is blended off by imperceptible degrees till it arrives at perfect light. — For instance, let *l m*, *fig.* 7., represent the luminous body or line from which the light proceeds, and let *a b* be the opaque object which it illuminates, then the umbra will be the space contained between the lines *l a c* and *m b c*, on both sides of which are the penumbræ, between *a c*, and *a d*, and *b c*, and *b f*.

Fig. 7.



Construction of the shadows in geometrical drawings. — Why the sun's rays are assumed to be parallel. — Complex shadows when there are several lamps in a room. — A shadow is invariably darker in proportion as the space by which it is surrounded is strongly illumined; hence the deepest shadow is always bounded by the brightest light. — Day and night upon our earth. — Shadows made by the sun and moon. The effects of the umbra and penumbra in card-board transparencies.

§ 280.

The *degree of illuminating power* possessed by the light which emanates from any luminous point depends

1) On the *distance* of the luminous body,
2) on the *absolute intensity* of the luminous body,
3) on the amount of the *absorption* the light suffers in its passage through the particular medium it has to traverse, and
4.) *on the angle at which the rays strike the surface of the object.*

§ 281.

In consequence of the propagation of light by radiation (§ 277.) it necessarily follows that the intensity of the light diminishes as the distance of the luminous body increases: the same law holds good in this instance as in all other cases of effects acting from a centre (such as gravity, § 29., and sound, § 260.), *viz. the intensity of the light diminishes as the square of the distance from the luminous body.*

The general expression of this law will be: $I = \frac{1}{D^2}$, I being the intensity and D the distance from the luminous body.

According to the preceding law, it would require four candles at a distance of two feet, or nine candles at a distance of three feet, to give as bright a light as one candle would afford at the distance of one foot. — If the distances of the planets from the sun be given, and the degree of light enjoyed by our earth be reckoned at unity, we can easily calculate by this law what will be the intensity of the light enjoyed by the other planets (supposing their atmosphere, &c. to resemble that of our earth). These proportions are presented to the eye at a single glance in the following table:—

Planets	**Mercury**	**Venus**	**Earth**	**Mars**	**Asteroids**	**Jupiter**	**Saturn**	**Uranus**
Distances	0·4	0·7	1	1·5	2·5	5	10	20
Intensity of Light.	6·25	2	1	0·44	0·16	0·04	0·01	0·0025

§ 282.

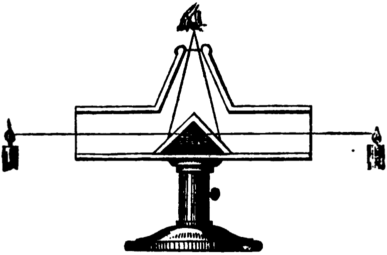
By this law we may also measure the relative illuminating powers of different sources of light: instruments which serve for this purpose are called *Photometers.* Those invented by Rumford and Ritchie are the best known, and are also the most simple in their construction. In Rumford's photometer the depth of the shadow is the measure used for comparing the intensities of different lights; in Ritchie's, the brightness of the illumination answers the same purpose. When the shadows are equally deep, or when the illuminations are equally bright, the luminous powers of the two sources of light will be as the squares of the distances at which they act.

A simple photometric apparatus, on Rumford's principle, consists of a white screen placed vertically, and at a small distance before it an opaque rod. To use it, place the lights, *ex. gr.* two different sorts of lamps, whose illuminating powers you desire to test, before the rod in such a manner that the shadows they project may either touch each other, or almost do so. The eye will readily perceive whether both the shadows have an equal depth; if they have not, move that light which casts the darker shadow to such a distance from the screen that the depth of both shadows shall become alike. Now, since the brightness of the screen is the product of the lights given by both the lamps, and since each shadow is enlightened by one of the lamps, it follows that their intensity will be equal when their shadows have an equal depth. When this obtains, measure the distances of the two lights from the screen, and their illuminating power will be directly as the squares of their distances.

Ritchie's Photometer consists of a rectangular box about an inch and a half or two inches across, and about eight inches in length, open at both ends, and blackened in the middle. In the middle of its longer dimension are two sheets of paper of equal whiteness, whose edges form with each other a right angle, but having an inclination of about 45° with the opening. A round hole is made in the top of the box, just where the two sheets of paper touch, so that the edges of the paper form the diameter of this circular aperture, in which a blackened tube is inserted. To compare two lights, place the instrument in such a manner between them, that each may enlighten one of the sheets of paper through the open ends, and move the instrument nearer to one or other of the lights, till both the papers appear to an eye looking at them down the tube to be equally bright. The intensities of the lights are to each other as the squares of their distances from the middle of the instrument. *Fig.* 8. represents such an instrument.

These photometers may also be applied to shew the truth of the important law laid down in the preceding §. Procure five wax-lights, of equal brightness, and place one at any distance whatever from the photometer, and the other

Fig. 8.



four at twice that distance; then it will be seen that the four candles, agreeably to the law, give a light only just equal to that of the single one. To obtain an equal illumination with one and two candles, they must be arranged so that their distances shall be as 5 : 7; for, in that case, their distances squared would be 5 . 5 = 25 and 7 . 7 = 49, or as 1 : 2 nearly. — Influence of the colour of light on all photometric experiments. — Besides the two philosophers already named, photometry has been greatly advanced by other scientific men, especially by Lambert, Bouguer, Wollaston, Herschel, Lampadius, and Leslie.

§ 283.

The brightness of two sources of light will depend, supposing them to be at equal distances from any object, on the *absolute intensity of their lights* (1) and on the *area of their luminous surfaces.* Their illuminating power is proportional to these two magnitudes and the effect they produce to the products of them (2).

(1) The absolute intensity of the light, or the luminous power of every physical point, is not to be confounded with the *apparent* or *relative* intensity, which depends on the distance of the luminous object from the observer.

(2) The general expression will be:

$$I = \frac{I' S}{D^2}$$

I being the relative, and I′ the absolute intensity; S the luminous surface, and D the distance.

Photometric experiments will prove the accuracy of this statement. To determine the absolute illuminating powers of two different luminous bodies, two candles, for instance, proceed thus:—Place the two lights which you desire to compare at equal distances from the open ends of a Ritchie's photometer. Interpose an opaque screen between the instrument and each of the lights; in each screen let there be an aperture of equal size exactly opposite the middle of the flame; the rays of light will therefore be projected from an equal superficies of the two candles, and if their illuminating powers are equal, the photometer will be as much enlightened by the one as by the other: if this is not the case, remove the stronger light with its screen, till both surfaces of the photometer seem equally bright. The absolute intensity of the two lights will be as the squares of their distances from the photometer.—Proceed in a similar manner to shew that with equal absolute intensities the degree of light enjoyed will vary as the surface of the luminous body. Procure two lamps of equal power and sufficient surface of flame, and also two screens, with apertures of equal diameter, provision being made for enlarging one of the apertures, so that its diameter may be doubled, and that, consequently, the opening in one screen may be made four times as large as that in the other. It will be seen that with equal apertures, at equal distances, the surfaces of the photometer will be equally bright; but if the aperture in one screen be enlarged, the surface opposite to it will be rendered more intensely light. Now, remove that light whose screen has the larger opening until the surfaces of the photometer become equally bright, and you will find that this distance will be exactly double the former; so that, with four times as great a luminous area, we obtain a fourfold intensity of light.

According to the corpuscular theory, the intensity of the light, arising from the two causes named above, depends on the force with which luminous matter is projected from the source of light, and also on the quantity of such matter set in motion: the explanation offered by the other theory is that the intensity of light, like that of sound, is owing to the magnitude of the vibrations excited by the luminous body, and on the mass of ether thus put into a state of luminous undulation. Other things remaining equal, the greater the excursions $a\,a'$, $f\,f'$, $b\,b$, &c. *fig.* 1., made by the atoms of ether, the more intense will be the sensation of light they produce; consequently, such a curve as a', f', b', g', &c. *fig*. 1., may serve as a graphic representation of the intensity of light.

The sun produces the strongest light with which we are acquainted on our earth: this is owing both to the great splendour of that luminary and to the extent of his disc.—The great influence which the size of a luminous area exerts on the intensity of the light is familiarly shown in the diminished glare there is in a room when the Venetian blinds are let down; the comparative gloom is owing solely to the smallness of the apertures through which the sun's rays are allowed to pass. The light which approaches most nearly in intensity to that of the sun is that which is given off at the charcoal points of a voltaic battery, and that given by the combustion of lime in oxy-hydrogen gas (Drummond's light). The feeblest light is that of burning hydrogen, that of a spirit lamp, and that of phosphorescent bodies. The very low illuminating power of these last, as compared with the light of the sun, may be shown by the following

Expt. Place some hydrogen in a state of combustion, or a spirit lamp, or a phosphorescent body, in the sunshine, and their light will cease to be visible.

If the fixed stars are luminous bodies, like the sun in our system, we may infer that the intensity of their light is little, if at all, inferior to his. Of the fixed stars the brightest is Sirius, and yet in the daytime he is no more visible to us than others of less brilliancy. The cause of this is the immense distance of all these bodies from our planet. Wollaston says, that by photometric experiments he has discovered that it would require 20,000 millions of such stars as Sirius to replace the light afforded by the sun, or that this luminary must be removed 140,000 times further from us than he is at present to reduce his light to that of Sirius. In a similar manner, this philosopher has determined that it would require 5563 wax candles, at the distance of one foot from an object, to produce a light equal to that of the sun; whereas the light of the full moon does not exceed that given by a single wax candle at a distance of 12 feet; whence the light of the full moon is only the $12^2 = 144$*th* part that of a wax candle at the distance of a foot. Again, moonlight is 5563 × 144 = 801072 times less than that of the sun.

§ 284.

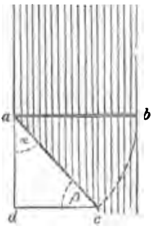
Since no perfectly transparent body exists on our earth (§ 275.), light must necessarily be impaired in its passage through all transparent media, and the diminution it suffers will vary as the medium is more or less transparent, and as the passage it makes is of greater or less length. The exact ratio in which light is diminished, has not yet been determined; it is, however, an established fact, that even those bodies which approach most nearly to perfect transparency, become opaque when their thickness is considerably increased.

According to Bouguer, the purest sea-water, at a depth of 730 feet, loses all its transparency, and the atmosphere in its clearest state would be altogether impervious to the sun's rays if it extended rather more than 700 miles. On this principle we can explain the diminished splendour of the sun and moon at the time of their rising and setting; for the nearer they are to the horizon, the longer is the passage and the denser the strata their rays will have to traverse. Whether the light would be similarly diminished if it passed through an absolute vacuum, or through space filled only with the ether, which is supposed to be universally diffused, we have no means of determining; however, the brightness with which the fixed stars shine, though at such immense distances from us, render this improbable.

§ 285.

Lastly, we have to investigate how much the intensity of light is modified according to the angle at which the rays impinge upon any object. A surface is most strongly illuminated when the rays of light fall perpendicularly upon it; and the greater the deviation of the angle of incidence from a right angle, the less the intensity of the light. This can be experimentally shown by presenting a white surface both perpendicularly and obliquely to the sun's rays.

Fig 9.



Let the fine parallel lines *fig.* 9. represent the sun's rays. It is clear that the surface *a b*, on which they fall perpendicularly receives the greatest possible number of rays, whilst any other position of the plane, as *a c*, is impinged on by a smaller number, in fact only by such a number as would have fallen on a plane at right angles to the rays, and having the length *d c*. But *d c* is sin. α, the angle of incidence, or cos. β the angle formed by the inclination of the plane with a perpendicular to the rays; whence in this case *the intensity of the illumination is as the sine of the angle of incidence of the rays, or, as the cosine of the angle made by the plane with a perpendicular to the rays.*

All that has been established in the preceding § §, with regard to the intensity of light, may now be comprised in the following general formula: —

$$I = \frac{I' S. \sin. \alpha}{D^2} \text{ or } \frac{I' S. \cos. \beta}{D^2}$$

I being the intensity, I′ the absolute intensity or illuminating power of the luminous body, S the superficies on which the rays fall, D the distance, α their angle of incidence, and β the inclination of the plane to a perpendicular to the rays.

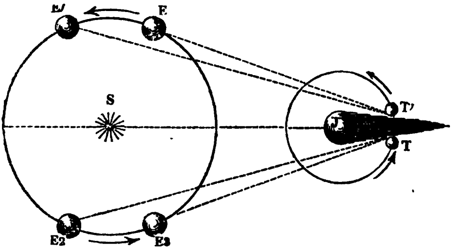
We shall explain presently how these results are affected by the character of a body's surface, and by the material of which it is composed.

§ 286.

Light travels at a prodigious rate; with a velocity, indeed, which, though it admits of being measured, yet so far exceeds all terrestrial velocities (see Table III. vol. i. p. 26.), that they are scarcely comparable with it. It was formerly believed that light moved with an infinite velocity, till, in the year 1676, the Danish astronomer, Olof Römer, found, from observations on the occultation of one of Jupiter's moons, that light moves through a space of about 192,000 miles in a second.

Herschel has calculated that light travels in a vacuum with a uniform velocity of 192,500 miles in a second. This velocity is the same for the waves of light excited by all the heavenly bodies; being in that respect analogous to the waves of sound, which are propagated in the atmosphere with equal velocities, whether the exciting notes be high or low, loud or weak. (§ 257.)

Fig. 10.

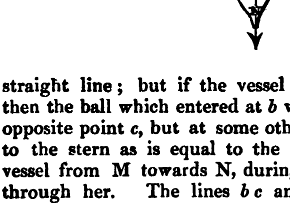


1.) Olof Römer found that when the earth in her orbit receded from Jupiter in a straight line, or in what approximated very nearly to one, as would happen if the earth were at E, *fig.* 10., then the emersion of Jupiter's first satellite T from the umbra of the planet J, would be visible about 15 seconds later than we should have expected, from the time the satellite would be occupied in performing that portion of its orbit about its primary. Now this satellite emerges from Jupiter's shadow, in about 42½ hours, or, more exactly, in 42 hrs. 28′ 35″; but in the same time the earth will have moved in her orbit from E to E′, *i. e.* about 2,880,000 miles; but light moves through this space in 15 seconds, consequently it travels with a velocity of 192,000 miles in a second. The converse obtains if the earth approaches Jupiter during the eclipse of the satellite, *i. e.* if she be moving in her orbit from E^2 to E^3.

Römer's discovery was confirmed by the observations of Dr. Bradley, in 1725, on the *Aberration* of Light. By aberration, we mean the alteration in the apparent positions of all the stars, owing to the velocity with which light moves, and to the motion of the earth in her orbit, in a direction which forms a tangent to the light from the heavenly bodies. In consequence of the aberration resulting from the combined operation of these two velocities, all the fixed stars appear to us to be rather more backward than they really are in the direction of the earth's annual motion.

The following explanation of this phenomenon is given by Eisenlohr, and also by Littrow, in his Die Wunder des Himmels, S. 189. Let M N, *fig.* 11. represent a ship whose side is aimed at point blank by a cannon at *a*. Now, if the vessel were at rest, a ball discharged in this manner would pass through the points *b* and *c*, so that the three points *a*, *b*, and *c* would be all in one straight line; but if the vessel itself move from M to N, then the ball which entered at *b* would not come out at the opposite point *c*, but at some other point *d* as much nearer to the stern as is equal to the distance gone over by the vessel from M towards N, during the passage of the ball through her. The lines *b c* and *b d*, therefore, form an angle at *b*, whose magnitude depends on the position of *b c* and *b d*; the greater the velocity of the ball as compared with that of the ship, the less the angle. Next, for the ship substitute in your mind the earth; and for the cannon, any one of the fixed stars. Let the velocity *b c* of the cannon-ball now stand for that of light, and let *d c* be the velocity of the

Fig. 11.



earth in her orbit, the angle dbc is called the *angle of aberration*. This angle has been found to be the same for all the fixed stars, *viz.* 20 seconds, or with greater accuracy 20·25 seconds; whence it appears that light travels with equal velocity through space from all these bodies. If now we suppose $\angle bcd$ to be a right angle, then

$$\text{tan. } \angle b : cd = \text{rad. } : cb;$$

that is,

$$\text{tan } \angle \text{ aberr. } : \text{ veloc. of earth} = \text{rad. } : \text{veloc. of light};$$

or,

$$\text{tan. } \angle 20{\cdot}25'' : 18{\cdot}963 = 10 : 195{,}000;$$

a result not materially different from that already obtained. This agreement in results arrived at by methods so dissimilar, proves both the accuracy of astronomical observations, and confirms us in the belief of the earth's revolution about the sun.

Light, at its mean velocity, takes about 8 minutes 13 seconds to come from the sun to our earth, and 2⅔ hours to travel from Uranus to our planet. It would require more than 6 years for light to traverse the space betwixt us and the nearest of the fixed stars; hence it follows that we never see these bodies in their actual position. The following illustrations may serve to give a comparative view of the velocity of light and that of other bodies: — A cannon-ball moving with a uniform velocity of 2450 feet in a second, would be 6½ years, and sound would be 14 years, in coming to us from the sun; a cannon-ball moving with the same velocity as we have already supposed, would be 16 hours in travelling round the circumference of our earth, a space which light traverses in ⅛th of a second: the velocity of light must therefore be ½ a million times greater than that of a cannon-ball, and more than a million times that of sound. At the rate of about 4 miles in 3½ minutes, being the speed at which Brunel, in 1841, travelled on the Great Western Railway, it would require more than 137 years to go from our earth to the sun.

III. CATOPTRICS, OR THE REFLECTION OF LIGHT.

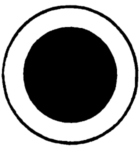
§ 287.

All opaque bodies possess the property of reflecting, to a greater or less degree, the light which falls upon them; they would not be visible to us, as has been observed already (§ 274.), were it not for their reflecting power.

The smaller the quantity of light any body throws back, the darker it appears to us; white surfaces reflect most light, and black the least. If a substance were absolutely black, it would not reflect any light at all, and would consequently be invisible to us; experience assures us that no such body exists.

Expt. Black velvet is one of the darkest substances with which we are acquainted, and one which seems to reflect no light. Blacken the inside of a tube, and look through it at a piece of black velvet; place over one of the ends of your tube a glass on which an opaque substance is fixed so as to leave only a small transparent ring, *fig.* 12. The light reflected from the velvet, will fall on the eye of the observer, showing that the material is not absolutely black, or incapable of reflecting the rays of light; for in that case the annular aperture would have been equally invisible with the opaque plate in the middle; this, however, is not the fact, and the surface of the velvet, instead of being black, has a greyish tint.

Fig 12.



§ 288.

If bodies have rough and uneven surfaces, the light which falls upon them will be *dispersed*, or irregularly reflected, by which means the surfaces thus impinged on by the light, will be rendered visible in all directions. If, on the contrary, the object be one presenting a smooth or polished surface to the rays of light which fall upon it, then, in this case, they will be reflected regularly; and when we look at such an object we shall see, not the object itself, but merely the image of the body by whose rays it is enlightened. Bodies which possess this property in a high degree are called *mirrors*, or *specula*.

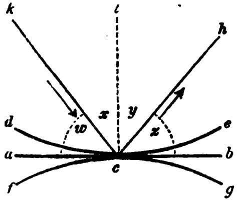
Specula are either *natural* or *artificial*; as instances of the former class we may mention the surfaces of liquids in a state of rest, which are indeed the most perfect specula that can be obtained; many crystals are also natural specula. Artificial specula are made either of metal or glass; the best metallic mirrors are made of platina, or an alloy of copper, silver, and zinc. Highly polished glass plates, blackened on one side, are found to answer well as specula for many purposes, so also are plates of obsidian or volcanic glass if one of their surfaces be well polished. Our common looking-glasses, which are covered on one side with an amalgam of tin, in order to form a reflecting surface, have this disadvantage, that we obtain a double reflection, one from the outer face of the glass, and a second from the metallic surface beneath.

Artificial mirrors are divided, according to the form of their surfaces, into *plane*, *convex*, and *concave*; according to the nature of the curve, they may be either *spherical*, *parabolic*, or *elliptical*; mirrors, with mixed surfaces, are either *cylindrical* or *conical*.

§ 289.

The following are the laws which obtain equally in the reflection of the rays of light from plane and from curved mirrors.

Fig. 13.



lc, Perpendicular to the plane.
x, Angle of incidence.
y, " reflection.
$x = y$
$w = z$

Let $a\,c\,b$, *fig.* 13, be the section of a plane speculum, and $d\,c\,e$, $f\,c\,g$ be sections of a concave and convex mirror, which both touch ab in c; let $k\,c$ be a ray of light impinging on these surfaces, $c\,h$ a ray reflected, and $l\,c$ the *normal* or perpendicular. Experience has shown that

1.) The normal, the incident, and the reflected rays all lie in the same plane, called the *plane of reflection*; and that it is at right angles to the reflecting superficies.

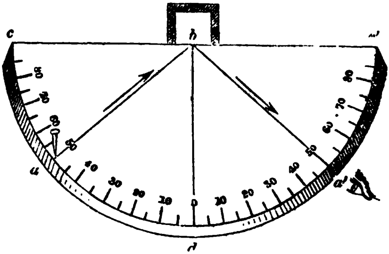
2.) *The angle of Incidence* x, and *the angle of Reflection* y, are equal, and they are on opposite sides of the normal; hence the incident and reflected rays form equal angles with the plane; and every ray falling perpendicularly on a mirror will be reflected back again on its own path.

3.) The reflection from concave and convex specula takes place as if the rays were received on a plane surface, standing as a tangent to the curve at the point where the normal touches the curve.

These laws may be verified by means of a very simple reflector.

First Expt. $c\,a\,a'\,c'$ *fig.* 14 is a semi-circular board, graduated at the circumference; at the centre b, place a small

Fig. 14.



looking-glass, vertically to the board; *d b* will then be the normal to the point *b*. Now, set up some luminous point (a common needle will do) at *a*, some 50° from *d*, and the ray *a b* will be reflected to *a'*, just 50° on the other side of *d*, parallel to the circular plane; from this point only would an observer be able to see the image of the object in the mirror.

Second Expt. Admit a ray of sun-light through a small aperture in the shutter into a darkened room, in such a manner that the light may fall upon a looking-glass. The whole course of the incident and reflected rays will be plainly marked on the particles of dust, which are illuminated by the sun, and thus experimentally confirm the truth of the law.

According to the corpuscular theory, the reflection of light obeys the same laws as regulate the impact of elastic bodies (§ 110), light, according to this hypothesis, being eminently elastic. The other explanation is, that the propagation of light takes place from every luminous point, by means of the undulatory movements of the ether: on this hypothesis the waves of light follow the general laws of the reflection of all elastic fluids; and, accordingly, every wave from every point, when it impinges on any resisting object so as to be reflected, forms a new wave in its course back, having its centre as much on the other side of the obstacle as the centre of the original wave was on this side; in the case of light, the centre of the original wave is obviously the luminous point. (Compare with this Echo, or the Reflection of Sound, §§ 218. 227.)

A. REFLECTION FROM PLANE MIRRORS.

§ 290.

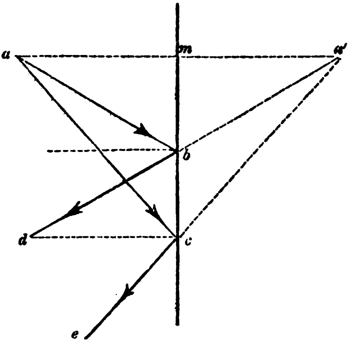
Agreeably to the laws of reflection, laid down in the preceding section, all the rays of light which fall upon any plane mirror, will be reflected in the same direction as that in which they impinged upon its surface; parallel rays of light will therefore continue parallel to each other after reflection; divergent and convergent rays will diverge and converge respectively with angles equal to their angles of incidence.

The accuracy of these observations may easily be shewn by a diagram drawn according to the laws given above.

Expt. Admit two parallel rays into a darkened room, so as to fall upon a plane mirror. They will be reflected from its surface in directions parallel to each other; if the rays be convergent, the reflex rays will intersect before the mirror; if they be divergent, they will be reflected so as to recede the one from the other.

All the rays from any radiating point that fall upon a plane mirror, are reflected from its surface in such a manner that they seem as if they proceeded from a point beyond the mirror; this point will be situated exactly where the reflected rays, if produced, would intersect each other, and it will be found to be as far beyond the mirror as the radiating point is before it; this point is called the *virtual focus*.

Fig. 15.



Let *m c*, *fig.* 15, be the vertical section of a plane mirror, *a* a luminous point before it, *a b* and *a c* two rays proceeding from it; *b d* will be the reflected ray of *a b*, and *c e* that of *a c*. Produce *d b*, *e c*, on the other side of the mirror, and these lines will meet in *a′*; *a′* is the virtual focus; and from the similarity of the Δs, *a b m*, *a′ b m*, and *a c m* and *a′ c m* respectively, it follows at once that $a' m = a m$.

According to the undulatory theory, a' is the centre of the reflected waves of light.

The image of any object, which may be regarded as merely the sum of its radiating points, will be as far behind a plane mirror as the object itself is before it; the size and form of the image will correspond exactly with the size and form of the object, with this difference only—that whatever is on the right side of the original will appear on the left in its image, and *vice versâ*.

The reversed appearance of any object seen in a plane mirror, is most strikingly illustrated, by holding a sheet of print or manuscript before such a mirror.

If a plane mirror be placed in a vertical position, then every object it reflects will be accurately portrayed, as regards its situation with respect to the horizon. If a plane mirror be inclined at any angle to an object, the object will appear behind the mirror inclined at an equal but opposite angle; consequently, an object lying flat will appear to stand perpendicularly if a mirror be placed at an angle of 45° to it; and conversely, an upright object will seem to lie down. — All these phenomena are well known, and may be easily verified by diagrams in which the laws of reflection are attended to, and experimentally by using a common looking-glass. — The *Polemoscope* is a perspective glass, having a reflector placed at an angle of 45° to its axis.—Mode of using this instrument. — If any one stands on a plane mirror, his feet and the feet of the image have their soles touching; if the mirror be held above the head, the figure will be inverted in that direction. — The reflection of objects in standing water presents us with similarly inverted pictures.

On this law of the reflection of plane mirrors depends the construction of several optical instruments; as, for instance, the *Heliostat*, the *Helioscope*, and the different kinds of *Goniometers*.

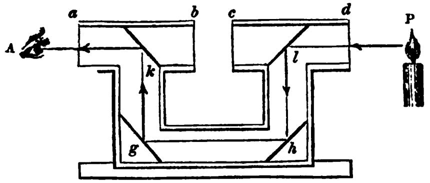
§ 291.

Further, the image produced by the first reflection may be reflected again by one or more mirrors. The image of an object, by this repeated reflection, becomes shifted in every direction, and may be multiplied many times by means of inclined mirrors placed opposite to each other.

To this property of light are owing: — 1.) The effects produced by the various kinds of magical perspective. These phenomena are owing to the parallel combinations of several plane mirrors at angles of 45° to the light which falls upon them.

First Expt. Fig. 16 is a sectional view of a magic perspective, by means of which objects may be seen, notwithstanding the interposition of a board, or other opaque screen, between the eye and the object.

Fig. 16.



a b c d is the perspective tube through which the observer is to look; it is divided at *b c*, so that a board, or any similar obstacle, may be interposed; notwithstanding which an eye at A will distinctly see any object at P.

The apparatus is thus constructed:—At *k* and *l* there are openings in the tube, by means of which a communication is established throughout the hollow pipe *k g h l*. At *k*, *g*, *h*, and *l*, looking-glasses are placed at angles of 45°. The line drawn in the interior of the tube represents the course of the reflected ray; the eye at A sees the object in the mirror, *k*, in the direction of A *k*, or A P.

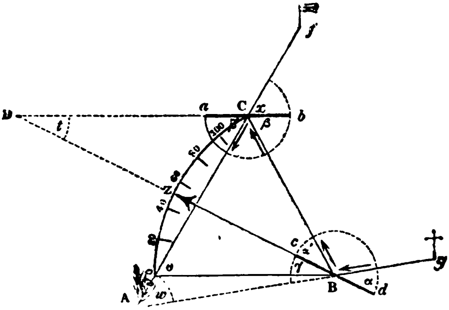
2.) If an object be placed between two plane mirrors, forming any angle whatever with each other, then the image will be repeated as many times. *minus* 1, as the angle made by the two planes is contained in 360°, *i. e.* putting n for the number of degrees contained in the angle, the number of images will be $\frac{360}{n} - 1$.

Second Expt. The *Kaleidoscope* invented by Sir. D. Brewster, is a well-known piece of apparatus; it consists of a tube about 10 inches long, and from 2 to 3 inches wide, blackened inside. Two or three pieces of looking-glass run through it lengthwise, generally forming angles of 60°. One end of the tube is closed by a piece of common glass, on it is fitted a continuation of the tube, the end of this additional piece being closed with ground glass; the space between these two glasses which is about ¼ of an inch, is filled with transparent coloured objects, pieces of coloured glass, and the like. The other end of the tube is also covered with a cap having a small aperture through which to look. If the tube be held with the ground glass end toward the light, and the eye be applied to the small aperture, the objects lying between the angles of the reflectors will be reflected five times, and the image of a regular hexagonal star will be formed.

Third Expt. Place two inclined mirrors on the drawing of a bastion, and you will have an image of a polygonal fortification.

3.) The application and use of *Sextants* and of Douglas's *Reflecting Circle*:—Both instruments serve, by means of two mirrors, one of which is moveable, to measure the angle made by two objects with the station of the observer.

Fig. 17.



The mirror *ab*, *fig.* 17. is fixed, but the mirror *cd* is moveable about B, and when in the position *o* B, it is parallel to the first mirror *ab*, and an arc that shall be drawn with B as its centre between the planes *b* D, B *o*, (the mirrors produced), would be the sixth part of a circle, whence the name of the instrument, the Sextant, is derived; the angle C B *o*, consequently, contains 60°. The side of the mirror *cd* is perpendicular to the index B Z; so, when the latter is moved from *o* towards C, the former is turned about its pivot B; and the index will show, on the graduated are, the number of degrees contained in the angle *o* B Z, *i. e.* the magnitude of the angle generated by the motion of *cd* from its original position.

Now suppose *dc* and *ba*, the planes of the mirrors, to be produced to D, the point of their intersection, then the angle *t* will mark the degree of their inclination; but as D C is parallel to B*o*, it follows that the angle *c* B *o* must be equal to the angle *t*, and can therefore be used equally with it to mark the inclination of the planes.

If we wish to measure from any station A, the angle which two objects, *g* and *f*, make with A, that is to determine the magnitude of the angle *w*, we should move the mirror *cd*, by means of the index B Z, until we brought it into such a position, that, whilst the eye at *o* sees the object *f* in the direction *o* C, the object *f* should also be seen in the mirror *ab* simultaneously with it, and in the same direction, its image having been reflected as shown by the lines γ B C *o*; then in

$$\Delta\,CDB,\ \angle t = \angle \beta - \alpha'$$

$$\text{and in } \Delta\,CBA,\ \angle w = \angle(\beta + x) - (\alpha' + \gamma).$$

Now, by the laws of Reflection:

$$\angle \alpha' = \angle \alpha \text{ in like manner } \angle \beta = \angle \beta'$$

$$\text{but (Eucl. I. 15.) } \underline{\angle \alpha = \angle \gamma} \quad . \quad . \quad . \quad . \quad . \underline{\angle \beta' = \angle x}$$

$$\text{whence } \angle \alpha' = \angle \gamma \text{ and } \qquad \angle \beta = \angle x;$$

whence it follows that,

$$\angle w = \angle 2\beta - \angle 2\alpha',$$

$$\text{and as } \angle t = \angle \beta - \angle \alpha'$$

$$\angle w = \angle 2t, \text{ or } \angle 2\mathrm{Z}\,\mathrm{B}o;$$ so the angle Z B*o* shown by the index, will be half the required angle *w*. In order to obtain the magnitude of angle *w* at once, without further computation, the arc of the sextant is divided into 120 parts, each of which expresses one degree of the angle *w*.

4.) The effects of mirrors hung parallel to each other in rooms: If an object stands between two looking-glasses hung parallel to each other, an image will appear as far behind each of the glasses as the object itself is before them. Each of these reflections produces a corresponding image in the opposite mirror, and so the object would be repeated *ad infinitum*, were not a portion of light absorbed with each successive reflection.

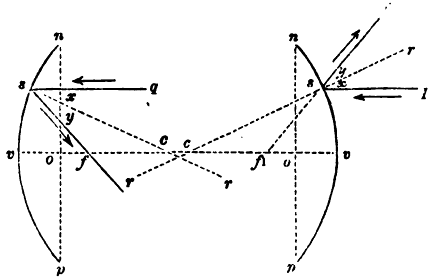
B. REFLECTION FROM CONCAVE AND CONVEX MIRRORS.

§ 292.

By *spherical mirrors* are to be understood such as are segments of a sphere; if their concavity be polished, they are called *concave* mirrors; if they reflect from their convex side, they are called *convex* mirrors.

In mirrors of this kind, *figs.* 18 and 19, *c*, the centre of that sphere of which the speculum is a segment, is called the *geometrical centre*, or the *centre of curvature*; whereas *v*, that point in the mirror's surface which is equidistant from all parts of its circum-

Fig. 18. *Fig.* 19.



f,	Focus.	*v c*,	Axis of the mirror.
v f,	Focal distance.	*c s*,	Radius of mirror.
c,	Geometrical centre.	*r c s*,	Principal ray.
v,	Optical centre, or vertex.	$x = y$.	

ference, is called the *optical centre* or *vertex* of the mirror. A right line *v c*, of unlimited length passing through these two centres is the *axis* of the mirror. All the radii of the sphere, as *c v*, *c s*, &c., are also *radii of the mirror's curvature;* and as they are perpendicular to the spherical surface, they, in fact, constitute the normals of the rays which fall on the points *v*, *s*, &c. of the mirror (§ 289.) Every ray from a luminous point *r* passing through the centre of curvature, as *r c s*, *r s c*, is termed a *principal ray*.

The reflection of light from every point of a spherical speculum obeys the universal law of reflection (§ 289.), that *the path of any reflected wave may be found, by assuming that the angle of reflection equals the angle of incidence.*

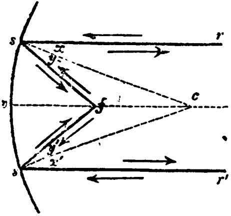
For instance, let *q s* be a ray impinging at *s* on the concave speculum, *fig* 18., and on the convex speculum, *fig.* 19., then in both cases *s f* will be the reflected ray, if $y = x$.

§ 293.

The rays of light will be variously reflected from the surface of a concave mirror, according to the direction in which they impinge upon it:

1.) All the rays that fall on a concave mirror in a direction parallel to its axis, will be reflected, so that each of them after reflection intersects the axis. If these rays be very near to the axis, they will cut it after reflection, in a point midway between the optical and geometrical centres, as appears from the construction of *fig.* 20. The point *f* is called the *focus*, and its distance *f v*, from the vertex of the speculum, is called the *focal*

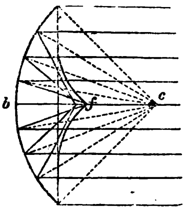
Fig. 20.



distance, and it is always equal to half the radius of that sphere of which the speculum forms a segment. The other points of the axis through which the reflected rays of light pass, are also termed *foci*, and their respective distances from *v* are called their *focal distances;* whence, for the sake of distinction, the *focus of parallel rays* is spoken of as the *principal focus*, and its distance from *v* as the principal focal distance of the mirror.

That parallel rays near to the axis of a concave mirror, and parallel to it, will be reflected so as to cut each other at the principal focus, may be deduced from *fig* 20., and the explanation accompanying. The limits within which it will be found that the reflection of the rays of light actually coincides with the statements made above, are rather narrow; as experience shows us that the parallel rays must not be more than from 10° to 15° from the centre of curvature, for if their distance exceed this, they will not be reflected so as to meet at the principal focus. In order that rays should be able, in the strictest sense of the term, to intersect each other, it is necessary that they should be equidistant from the axis; and the greater their distance from the axis, the nearer will their points of intersection approach the surface of the speculum. This is shown in *fig.* 21. This deviation of the rays is termed the *Aberration of Sphericity;* the lines formed by the reflexion of the rays are termed *caustic curves;* and the rays, instead of meeting in a point or focus, are spread over a small space. In mirrors of a parabolic form this aberration does not obtain, but parallel rays do actually all unite in the focus of the parabola. (Compare with this § 219.)

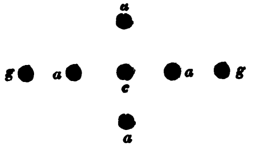
Fig. 21.



First Expt. The following method will very plainly illustrate the reflection of parallel rays.

Make from four to six holes about two lines in diameter, in a plate of iron, tin, or some other metal, of a sufficient size to close up a large aperture in the window-shutter of a dark room; let these holes be arranged as shown at *a*, *fig.* 22; exactly in the middle let there be another opening *c* of the same diameter; and still further, let there be two more similar apertures *g*; some arrangement must be made for opening and closing them at pleasure. The rays of light which pass through these apertures will be parallel to each other. Now, place a concave mirror in such a manner that the ray transmitted through *c* shall impinge on the vertex *v*, see *fig.* 21., so as to be perpendicular to it; next, open successively the holes *a*, and each of the rays passing through them will be so reflected as to intersect the axis *cv*, in the principal focus *f*; indeed, the rays will form a pyramid, whose base rests on the speculum, and whose vertex is at *f*. Lastly, admit the light through the holes *g*, which are more remote from the axis; and it will be found that their rays striking the mirror nearer to its boundary, will be so thrown back as to intersect the axis somewhere between the focus and the surface of the mirror. If it is wished to give very great distinctness to the individual rays of sun-light, they may be made to pass through the smoke of a chafing-dish.

Fig. 22.



Second Expt. A cylindrical mirror will be found the best calculated to display the caustic curve; it is merely a hollow semi-cylinder, and may be conveniently made of a strip of polished tin, or of a pretty wide piece of polished clock-spring, held in form by a semi-circular board covered with white paper. If the speculum be presented to the rays of the sun or to those of a candle, a luminous space will be visible on the paper, bounded by a line resembling the curve in *fig.* 21.

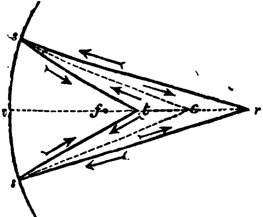
If a parabolic curve be imparted to the metal, then the brightest speck will be at its focus, whence rectilinear rays will proceed resembling a star.

2.) All diverging rays from a radiant point, situated in the focus of a concave mirror, will be reflected from its surface in directions parallel to each other, and to the axis; provided that their distance shall not exceed 10° or 15° from the vertex. Such reflected rays will consequently not intersect each other.

This is merely the converse of the preceding law; the truth of it will be at once seen on referring to *fig.* 20.

3.) All rays proceeding from the centre of curvature, or which pass through such centre, that is to say, all the principal rays, fall perpendicularly on the surface of the speculum, and are therefore reflected to the centre.

Fig. 23.

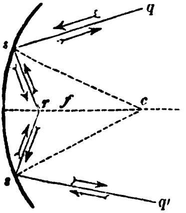


4.) Rays, on the contrary, which come from any point, as *r*, *fig.* 23, beyond the centre of curvature, or which cross the axis at a point beyond such centre, will be reflected so as to cut the axis somewhere, as *e. g.* in *t*, between the focus and the centre of curvature.

5.) Conversely, if rays intersect the axis at any point *t*, *fig.* 23, between the focus and the centre of curvature of a concave speculum, then they will be reflected so as to cut the axis again in another point, beyond such centre. See the direction of the arrows in *fig.* 23.

6.) Lastly, all rays coming from any point *r*, *fig.* 24, between the mirror and the focus, will be reflected from its surface so as to diverge from the axis.

Fig. 24.

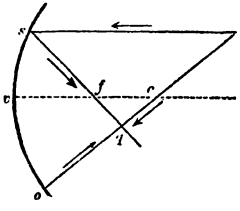


§ 294.

If there be any radiant point before a mirror, the virtual focus of that point may be found (§ 290.) by producing the reflected rays until they meet.

If, then, we are able to determine where two reflected rays will intersect each other, we can at once ascertain the situation of the virtual focus. From every radiant point there proceeds an infinite number of rays, but of these, two only are, for the most part, made use of, in determining the situation of the virtual focus; they are one principal ray, which is reflected on its own path, and one of the rays parallel to the axis, which, when reflected, passes through the focus. The intersection of these two rays gives the virtual focus required.

Fig. 25.



It is not absolutely necessary to use a ray parallel to the axis; any other will do, only it must be observed that its reflected ray cannot be determined so easily as that of a parallel ray.

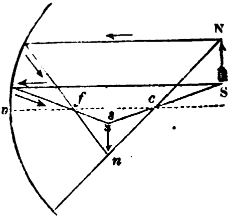
Let *o s*, *fig.* 25, be a concave mirror, and *r* any radiating point before it; draw *s q* through the focus *f*, as the reflected ray to *r s;* and from *r* draw *r o*, through the centre of curvature; *q*, the point of intersection of these two rays, is the virtual focus of *r*. The virtual focus of every luminous point in the axis of a concave mirror will be in the axis; and that of any point on one side of the axis, will be found on the opposite side of it.

To determine the situation of the image of an object reflected by a concave mirror, we must find the virtual foci of the points in the object's boundary.

§ 295.

The following are the phenomena presented to us by the reflection of the rays of light which impinge on concave mirrors:—

Fig. 26.

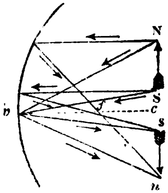


1.) The image of an object very remote from the mirror, as that of the sun, will be in the focus of the mirror, and the image will be extremely small.

2.) Every object which is at a distance from the mirror greater than its centre, produces an image between this point and the focus, smaller than the object itself, and in an inverted position. (See *fig.* 26.)

3.) If the object be at a distance from the mirror equal to the length of its radius, as N S, *fig.* 27, then the image *n s* will be at an equal distance from the mirror; its dimensions will be the same as those of the object, but its position will be inverted, as is shown in *fig.* 27.

Fig. 27.



4.) If the object be between the focus and the centre of curvature, as *n s* in *fig.* 26, then the image will be inverted, and its size will much exceed that of the object; its place, also, will be beyond the geometric centre, as N S.

These four varieties of inverted images, produced by the reflection of the rays of light from concave mirrors, are sometimes called *physical spectra.*

The existence and position of these spectra may easily be shown experimentally, thus:—

Expt. Hold a candle opposite to a concave mirror at the distances named respectively in paragraphs 1.), 2.), 3.), 4.) on the preceding page. The spectrum can in each case be received on a white screen, which must be placed at the prescribed distance from the mirror.

Application of these spectra in different optical instruments, as reflecting telescopes, &c.

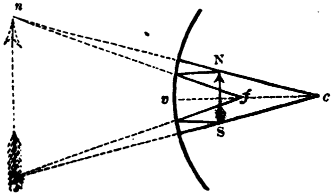
5.) If a luminous body, as, for instance, the flame of an Argand lamp, or a burning coal, be placed in the focus of a concave mirror, no image will be produced, but the whole surface of the mirror will be illuminated, because (2. § 293.) it reflects in parallel lines all the rays of light that fall upon it.

This may be made the subject of an experiment so simple as not to require any further explanation.

Practical application of this fact, in the *reflectors* of microscopes, magic lanterns, and lighthouses, by means of which the light given by the luminous body is increased and transmitted in some particular direction that may be desired.

6.) Lastly, place the object between the mirror and the focus, as N S, *fig.* 28, and the image of the object will be behind the mirror; it will not be inverted, but its proportions will be enlarged according to the proximity of the object to the focus. In this case the reflected rays (5. § 293.) diverge, and consequently intersect behind the mirror, so that they appear as if they really proceeded from these points of intersection. *Fig.* 28 will at once illustrate these remarks.

Fig. 28.



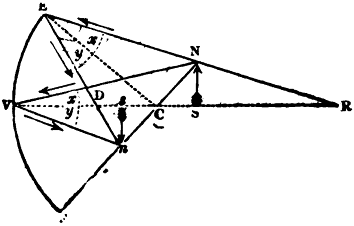
The truth of this last proposition admits of being experimentally tested.

Concave mirrors, from the property last-named, are sometimes called *magnifying mirrors ;* and because, by collecting the sun's rays into a focus, they produce a strong heat, they are called *burning mirrors.*

[We shall now proceed to give a simple demonstration of what has been advanced in the present and two preceding §§.

Let F E, *Fig.* 29, be a sectional view of a concave mirror, V its vertex; C the centre of the circle; C V, C E, C F $= r$ radii of the mirror. Let R be any radiant point in the axis, R V $=$ a, its distance from the vertex. Let R E be an incident ray, E D the reflected ray, and $VD = a$ the focal distance.

Fig. 29.



$$\text{Since } \angle x = \angle y,$$

$$\therefore ED : ER = CD : CR, \qquad \text{[EUCL. vi. 3.]}$$

and if $\angle VRE$ be very small,

$$\therefore RE = RV = \mathrm{a} \text{ nearly},$$

$$\text{and } ED = VD = a \text{ nearly}$$

$$\therefore VD : VR = CV - VD : VR - VC,$$

$$\text{or } a : \mathrm{a} = r - a : \mathrm{a} - r;$$

$$\therefore a\,\mathrm{a} - a\,r = \mathrm{a}\,r - \mathrm{a}\,a,$$

$$\therefore 2\,a\,\mathrm{a} = \mathrm{a}\,r + a\,r;$$

$$\therefore \frac{2}{r} = \frac{1}{\mathrm{a}} + \frac{1}{a}. \qquad \text{(I.)}$$

Let $\mathrm{a} = \infty$, *i.e.* let the distance of the radiant point be infinite, or, in other words, let the rays be parallel; then $\frac{1}{\mathrm{a}}$ vanishes, and there remains

$$\frac{2}{r} = \frac{1}{a}$$

$$\text{or } \frac{r}{2} = a = f,$$

that is, the focus f lies in the middle of the radius; and therefore equation (I.) becomes

$$\frac{1}{f} = \frac{1}{\mathrm{a}} + \frac{1}{a} \qquad \text{(II.)}$$

If the radiant point R lie out of the axis, as at N, its position may be determined by knowing its abscissa $VS = \mathrm{a}$ and its ordinate $SN = b$.

Let the rays from N make with the axis a very small angle, then their focus n, will be given by the following equations:—for, let $\mathrm{V}s = a$, $sn = \beta$

$$1.)\ \frac{1}{f} = \frac{1}{\mathrm{a}} + \frac{1}{a}.$$

$$2.)\ \beta = \frac{a}{\mathrm{a}} \cdot b.$$

For, produce the ray E N till it meets the axis in R; then V D is the focal distance of the point R, and by equation (II.) we have

$$\frac{1}{f} = \frac{1}{\mathrm{a}} + \frac{1}{a} = \frac{1}{\mathrm{VR}} + \frac{1}{\mathrm{VD}} \qquad \text{(A.)}$$

Now, if we consider VE to be so small an arc that it may be assumed as a right line, and

$\because \triangle$ s, VED, and D sn, are sim.

$$\therefore \mathrm{VE} : \mathrm{VD} = sn : s\mathrm{D}$$
$$= \beta : a - \mathrm{VD};$$
$$\therefore \mathrm{VE}\,.\,a - \mathrm{VE}\,.\,\mathrm{VD} = \beta\,.\,\mathrm{VD},$$
$$\therefore \mathrm{VD} = \frac{a\,.\,\mathrm{VE}}{\beta + \mathrm{VE}},$$
$$\therefore \frac{1}{\mathrm{VD}} = \frac{\beta}{a\,.\,\mathrm{VE}} + \frac{1}{a}.$$

Again, $\because \triangle$ s, V E R, and S N R are sim.

$$\therefore \mathrm{VE} : \mathrm{VR} = \mathrm{SN} : \mathrm{SR},$$
$$= b : \mathrm{VR} - \mathrm{a},$$
$$\therefore \mathrm{VE}\,.\,\mathrm{VR} - \mathrm{VE}\,.\,\mathrm{a} = b\,.\,\mathrm{VR},$$
$$\therefore \mathrm{VR} = \frac{\mathrm{a}\,.\,\mathrm{VE}}{\mathrm{VE} - b},$$
$$\therefore \frac{1}{\mathrm{VR}} = \frac{1}{\mathrm{a}} - \frac{b}{\mathrm{a}\,.\,\mathrm{VE}}.$$

Substituting these values in equation (A.), we have

$$\frac{1}{f} = \frac{1}{\mathrm{a}} - \frac{b}{\mathrm{a}\,.\,\mathrm{VE}} + \frac{\beta}{a\,.\,\mathrm{VE}} + \frac{1}{a}$$
$$= \frac{1}{\mathrm{a}} + \frac{1}{a} + \frac{1}{\mathrm{VE}}\left(\frac{\beta}{a} - \frac{b}{\mathrm{a}}\right). \qquad \text{(B.)}$$

And since $\triangle$ s, V S N, and V $s\,n$, are sim.

$$\therefore ns : \mathrm{V}s = \mathrm{NS} : \mathrm{VS},$$
$$\text{or } \beta : a = b : \mathrm{a},$$

$\therefore \beta = \dfrac{a}{\mathrm{a}} \cdot b$, which is equation 2.)

and $\because \dfrac{\beta}{a} = \dfrac{b}{\mathrm{a}}$

$$\therefore \frac{\beta}{a} - \frac{b}{\mathrm{a}} = 0;$$

∴ equation (B.) becomes

$$\frac{1}{f}=\frac{1}{\mathrm{a}}+\frac{1}{a} \text{ which is equation 1.)}$$

Consequently, all the rays from a point N without the axis falling on the mirror, will be reflected thence, so as to meet at *n* and form a cone of light whose vertex is in the principal ray.

From what has been shown above it follows, that if S N, *fig.* 29, be any object whatever, *s n* must be its image, whose linear magnitude may be found from equation 2., $\beta = \frac{a}{\mathrm{a}}\cdot b.\Big]$

Before a concave mirror, having a focal distance f of 6 inches, place at a distance of 24 inches $=\mathrm{a}$, an object whose height is 6 inches $=b$; it is required to determine the distance a of the image from the mirror, and also its height β. — From equation 1.,

$$\frac{1}{a}=\frac{1}{f}-\frac{1}{\mathrm{a}}$$

$$=\frac{1}{6}-\frac{1}{24}$$

$$=\frac{1}{8},$$

or $a = 8$ inches.

$$2., \beta=\frac{a}{\mathrm{a}}\cdot b$$

$$=\frac{8}{24}\cdot 6,$$

or $\beta = 2$ inches.

Further, we obtain from equations 1. and 2.,

1.) Where an object is at an infinite distance, *i.e.* when $\mathrm{a} = \infty, \frac{1}{\mathrm{a}} = 0$, we shall have $a=f$; in other words, the image will be a mere point in the focus.

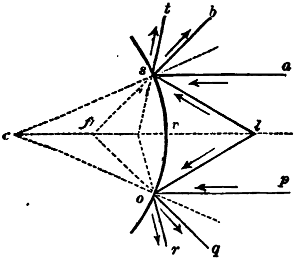
2.) As a decreases a increases; *i.e.* the nearer any object is brought to the centre of curvature, the further is its image thrown back towards itself, and the larger does that image become; so that when $\mathrm{a}=r$, then will $a=r$ also: whence, at the distance of the centre of curvature, the image will be equal to the object.

3.) Now move the object nearer to the focus and its image will constantly recede from the centre of curvature and become larger and larger. If $a=f, \frac{1}{a}=0 \therefore a=\infty$; *i.e.* the image of an object situated in the focus, will be at an infinite distance from the mirror, or rather, no image whatever will be formed, for the reflected rays will be parallel.

§ 296.

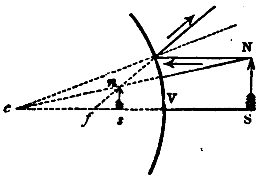
In *convex* mirrors the focus f', *fig.* 30, lies as far behind the reflecting surface as in concave mirrors it lies before it; it is generally called the *virtual focus* (because it is only an imaginary point and is not formed by the actual union of rays in a focus). — All rays parallel to the axis which fall on a convex mirror, as *a s*, *p o*, on being reflected will diverge, as *s b*, *o q*, as if they proceeded from f' as a focus. — Diverging rays, like *l s*, *l o* will after reflection be still more divergent, as *s t*, *o r*, as if they proceeded from some point between the virtual focus and the mirror.

Fig. 30.



The position of the image of any radiating point whatever, and consequently the entire image of an object, may be found in a manner similar to that already explained in the case of concave mirrors (§ 294.). See *fig.* 31.

Fig. 31.



The following effects obtain in the reflection of rays from spherical convex mirrors: —

1.) The images of objects invariably appear beyond the mirror; in other words, they are virtual images:

2.) They are seen in their natural position: and

3.) They are smaller than the objects themselves; the farther the object is from the mirror, and the less the radius of the latter, the smaller will be the image. If the object be very remote, its image will be in the virtual focus of the mirror.

The same mathematical deductions hold good for mirrors of this class as for concave mirrors (§ 295.), observing only that in this case r is *negative*:

$$-\frac{2}{r}=\frac{1}{\mathrm{a}}+\frac{1}{a},$$

and

$$-\frac{1}{f}=\frac{1}{\mathrm{a}}+\frac{1}{r}.$$

1.) When $\mathrm{a}=\infty$, *i. e.* when an object is at an infinite distance from the mirror $a=-f$.

2.) If a diminishes, a must diminish also; thus, when $\mathrm{a}=r$, $a=-\frac{r}{3}$.

3.) When $\mathrm{a}=0$, $a=0$; *i. e.* the object and its image will fall together on the mirror.

§ 297.

Cylindrical and *Conical mirrors* act like plane ones in the direction of their axis, but in a direction perpendicular to the axis they act like spherical mirrors. If such a mirror be placed vertically, the image of any object will be of the same length as the original; but its breadth will be exaggerated or reduced, according as the convex or concave surface is polished. If the mirror be laid horizontally, these circumstances will be reversed.

A conical mirror differs from a cylinder in this, that its surface in the direction perpendicular to the axis, consists of an infinite number of spherical mirrors, of gradually decreasing sizes towards the vertex; whereas, in the cylinder, planes passing through the axis and parallel to the horizon, would give equal circles throughout. If such a mirror be placed in a vertical position, an object seen in it would appear of its natural length, but its breadth would gradually taper off towards the vertex.

From what has been just stated it is evident, that these mirrors do not represent objects in their natural proportions; if, therefore, any object appears in such a mirror to be of its just dimensions, the original drawing must have been distorted according to regular laws, in order to produce this effect; these pictures as well as their reflected images in the mirrors are termed *catoptric anamorphoses.*

§ 298.

It has been already (§ 287.) remarked, that all bodies whatever reflect more or less of the light which falls upon them. By means of Ritchie's Photometer (§ 282.) we can compare the intensities of the incident and of the reflected light. It has been ascertained that the intensity of light reflected perpendicularly from a metallic speculum is about $\frac{2}{3}$, from mercury $\frac{1}{2}$, from water $\frac{1}{55}$, and from glass $\frac{1}{40}$ that of incident light; and that the proportion becomes less, the more oblique the angle at which the rays fall. This diminution of the light is owing to its absorption by the reflecting body: from these considerations it follows that metallic specula are the best reflectors.

IV. THE REFRACTION OF LIGHT.—DIOPTRICS.

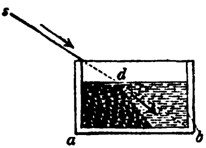
§ 299.

When a ray of light passes out of one transparent medium into another, either differently constituted, or of a density differing from that of the former, then the ray will either continue its course in the same path as before, or it will travel in a new direction. If it impinge perpendicularly on the plane by which the medium is bounded, its direction will not be altered; if, on the contrary, it strikes the plane at any other than a right angle, it will be diverted from its original course. This deflection of the rays of light is termed *Refraction*.

First Expt. Admit a ray of sun-light in such a manner into a darkened room that it may fall obliquely on a cubical piece of glass; a piece of plate glass will do if of sufficient thickness. The direction of the ray will be changed on its entering the glass.

Second Expt. Let a shadow of the width *a b*, *fig.* 32, fall on the bottom of any opaque vessel. Fill the vessel with water, and the shadow will acquire the tapering form represented in the cut, in consequence of the ray *s b* being refracted at *d* towards *c*.

Fig. 32.

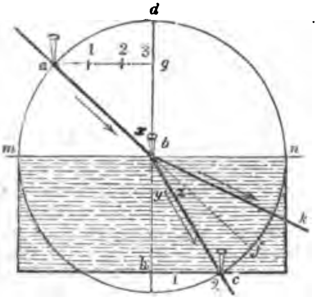


A similar result will be obtained by placing a thick glass plate at the bottom of a square box.

Third Expt. Lay a coin, or any similar bright substance, at the bottom of an opaque vessel, as an earthenware basin, and place the whole at such a distance that the edge of the vessel just hides the piece of money from your view. Pour in water, or lay a bit of thick plate glass, upon the coin and it will again become visible.

It is in consequence of the refraction of light that straight posts, standing upright in smooth water, look as if they were broken at the surface of the fluid; for a similar reason the bottom of a vessel containing water, or the bed of a clear stream, seems to us at a less depth below the surface than we know it actually to be.

Fig. 33.



Let *m n*, *fig.* 33, be the plane of intersection between two transparent media, as *e. g.* air and glass, or air and water; and let a ray fall obliquely, as *a b*, upon this surface Refraction will ensue; that is, the ray will take the direction either of *b c* or *b k*: *b* is called the *point of incidence*; *m n* is the surface where the two media are in contact, and is not necessarily a plane, though represented as such in the diagram for the sake of simplicity: *d e* is the *perpendicular*; *x*, the *angle of incidence*; and *y*, or *k b c*, the *angle of refraction*, according as the ray is bent towards the perpendicular or from it: $z = cbf$, or *f b k*, measures the deviation of the ray from its original course. With *b*, the point of incidence, as a centre, describe a circle; and from *a* and *c* draw *a g* and *c h* at right angles to the perpendicular *d e*, then *a g* is the *sine of the angle of incidence*, and *h c* the *sine of the angle of refraction*: the ratio of the former to the latter is the ratio of the ray's refraction.

§ 300.

The laws which have been deduced by experiment concerning the refraction of light, are the following: —

1.) Every ray is refracted *toward* the perpendicular in passing out of a rare into a dense medium; when these circumstances are reversed, it is refracted *from* the perpendicular. Of two media that is said to have the *greater refracting power*, in which the light is refracted towards the perpendicular.

Thus, for instance, when light passes from air into water or glass, it is refracted towards the perpendicular; when from either of these substances into air, the ray is inclined from the perpendicular. If light comes from a vacuum into any transparent medium whatever, refraction takes place towards the perpendicular.

2.) *The incident ray, the perpendicular, and the refracted ray lie in one and the same plane,* termed the *plane of refraction,* which stands at right angles to the plane where the two transparent media are in contact.

3.) *The incident and the refracted rays are invariably on opposite sides of the perpendicular.*

4.) *In the same medium the angle of refraction continues always the same.*

The refractions which come most frequently under our notice, and whose proportions it therefore concerns us most to know, are those of air and glass, and air and water. The ratio between air and glass is nearly 3 : 2 (or more exactly, 17 : 11); between air and water, very nearly 4 : 3.

The accuracy of the above proportions may be shown by a very simple experiment.

First Expt. Procure a board which may be made either circular or square; if the latter, describe upon it a circle *fig.* 33, and draw the two diameters $m\,n$, $d\,e$ at right angles to each other. Next in the two semi-circles on opposite sides of $m\,n$, make two angles x and y, such that their sines $a\,g$ and $h\,c$ shall be to each other, as 3 : 2. In each of the three points a, b, and c of the crooked line, fix a bright body, as a pin or a needle; and between $m\,n$ and $h\,c$ set a piece of glass about an inch in thickness; when, in consequence of the refraction of the light, all the three pins will appear to be in one straight line. Next, let the sines be to each other as 4 : 3; immerse the lower half of the plane to $m\,n$ in water, and the pins, as before, will be seen in a straight line.

The ratio of refraction $\frac{1}{n}$ is commonly expressed by a fraction, having for its numerator the sine of the angle of incidence x of a ray supposed to proceed from a vacuum, and for its denominator the sine of the angle of refraction y, in the particular medium in question (*fig.* 33.). This fraction $\frac{1}{n} = \frac{\sin. x}{\sin. y}$ is then converted into a decimal, and expresses the magnitude of the *index* or *exponent* of a body's *refracting power.*

The following table will show the refractive power of some of the principal transparent bodies: —

	Index of Refraction.
Vacuum	1·000000
Hydrogen	1·000138
Oxygen	1·000272
Azote	1·000300
Atmospheric air, at a mean density	1·000284
Olefiant gas	1·000678
Ice, a mean	1·3077
Water	1·3[illegible]6 3
Alchol	1·372
Oil of turpentine	1·470
Calcareous spar, ordinary refraction	1·6543
Ditto, extraordinary refraction	1·4833
Crown-glass, English	1·500
Ditto, Frauenhofer's, a mean	1·532
Rock-crystal	1·562
Flint-glass, Dollond's	1·584
Ditto, Frauenhofer's, a mean	1·639
Sulphur, natural	2·040
Phosphorus	2·224
Diamond	2·439 to 2·487
Chromate of lead	2·936

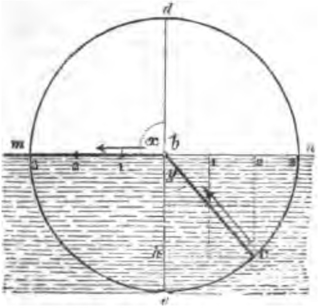
The last-named body has the highest refractive power; and the indices of the refraction of all known substances range, as the preceding table shows, between 1 and 3.

No law has yet been discovered by which the different refractive powers of bodies are regulated; as a general rule it would appear, that dense bodies have a greater refractive power than such as are more rare, and that this power increases in the same substance when its density is increased; this may be observed in the case of gases. This property, however, does not depend solely on a body's density, but is in part influenced by its chemical composition; thus it has been noticed that inflammable bodies refract light more strongly than such as are incombustible.

5.) The refraction of light is converted into its total reflection, if it passes out of a highly refractive medium into one that is less so and makes the angle of incidence so large that the angle of refraction exceeds 90°. If the angle of incidence be exactly such as to make the angle of refraction a right angle, then the ray will be propagated with increased intensity, in the direction of the plane bounding the refractive medium.

Let *m n*, *fig.* 34, be the surface of a piece of glass which is represented by the parallel lines in the diagram, the portion above *m n* being supposed to be air; then the ratio of

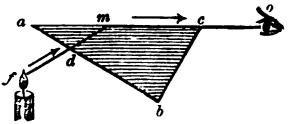
Fig. 34.



the refractions of these two bodies is $\frac{3}{2}$, and the sine of the angle of incidence $y = hc$ will be $\frac{2}{3}$ of radius bn; whence the angle of refraction $x = \frac{2}{3} \cdot \frac{3}{2} = 1 =$ radius bm; *i. e.* the light goes from b in the direction bm. In this case $y = 41° 48' 37''$; for water the angle of *total reflection* as it is called is $48° 27' 40''$. If angle y be greater, the reflection from b obeys the ordinary laws.

Second Expt. The total reflection of light may be thus shown by means of a glass prism. Cover the two sides *ab*, *bc*, *fig.* 35, composing the right angle, with black paper, leaving a small round aperture in one of the covered sides for the admission of a ray of light. Place the prism in such a position that the ray *f m*, from the luminous body at *f*, may strike the opposite uncovered face of the prism *a c*, at such an angle that it will be refracted in the direction *m c*, when an observer at *o* would see the total reflection.

Fig. 35.



Third Expt. Lay a new coin or other bright object at the bottom of a sufficiently wide glass vessel, and pour in water till it rises to a depth of two or three inches, and the ordinary reflexion may be seen at the bottom of the water, if the glass be held obliquely above the eye of the observer.

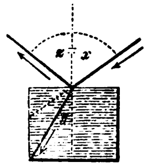
Fourth Expt. Lay a prism on a sheet of written or printed paper, and look perpendicularly down upon it, and the words will be clearly seen through the glass. Bring your eye gradually down towards one side of the prism, and the writing or printing will become invisible, whilst the underside of the prism, acting like a mirror, will reflect with the greatest distinctness images of such objects as may be situated opposite to the prism.—Practical application of the prism in consequence of its possessing this property, in the construction of the Camera lucida.

6. When light passes out of any transparent medium whatever into another, the whole is not transmitted, but some portion of the light is reflected, for which reason there cannot exist any perfectly transparent medium. (§ 276.)

Hence the reflection of water and other transparent fluids, as also that of glass, even when it is not silvered.

Fifth Expt. Admit a ray of sun-light into a darkened room, so that it may be received on a cube of glass, or on the surface of some water in a glass vessel. At the point of incidence there will be a simultaneous reflection and refraction of the ray, as represented in *fig.* 36.

Fig. 36.



The following general formulæ, which express the relation that subsists between the reflection and refraction of light in bodies, were deduced by Poisson from theory, and they have been found in many instances to accord with the results obtained by experiment:—

If $\frac{1}{n}$ be the ratio of refraction for any transparent substance, then the intensity of light falling perpendicularly will be as $1 : \frac{(1-n)^2}{(1+n)^2}$; that of light entering the body and becoming refracted, $\frac{(4n)^2}{(1+n)^2}$.

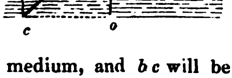
§ 301.

As the nature of light itself is but imperfectly known by us, we can only hypothetically explain the causes which produce refraction.

According to the corpuscular theory, refraction is accounted for on the supposition that media of different characters and densities exert an attractive influence on those rays of light which approach their respective boundaries. According to this view, a *highly refractive medium* is one that exerts a powerful attraction on the particles of light which come in contact with it, and a less *refractive medium* is one that attracts the particles more feebly, in the former case accelerating, in the latter, retarding their velocity. If a ray of light fall perpendicularly on a highly refractive medium its direction is not altered, but the velocity with which it is propagated is increased; if it strike the medium obliquely, it will be drawn towards the perpendicular by means of the supposed attraction, which, it is assumed, acts at right angles to the plane of incidence. The converse obtains when the ray strikes on a less powerfully refractive medium; for the attraction of that from which it has come is greater, and consequently the ray is more strongly drawn towards the medium it has left than towards the one it has entered, *i.e.* it recedes farther from the perpendicular.

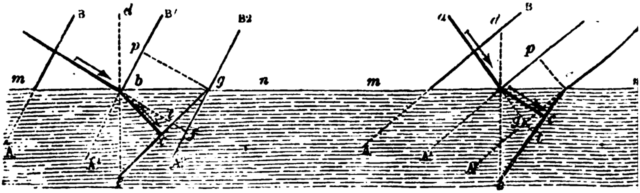
The following explanation may, perhaps, render the preceding remarks more intelligible. Let *s b*=*b t*, *fig.* 37, represent the velocity and direction of light in the medium whence it comes to strike the surface *n m* of a second medium; *s b*=*b t* may then be regarded as the resultant of the two forces *k b*, *b h* (§ 23.). If now the second medium have a stronger attraction than the former, the component *b h* will be greater; let *b o* represent this force, then the resultant will be *b c*, in which case the ray is attracted towards the perpendicular; next, let the second medium have a less refractive power, then the component *b h* will be diminished, let *b p* be the attraction of this medium, and *b c* will be the resultant of the two forces *k b*, *b p*, whence it appears that the ray is inclined from the perpendicular.

Fig. 37.



According to the undulatory theory, the refraction of light is to be attributed to a change in the velocity with which the particles of ether vibrate, exactly reversing the assumption of the other hypothesis; for the ether is supposed to move most freely, and to possess the greatest elasticity in vacuo; in every other transparent medium its mobility and elasticity are impaired by the presence of a material substance, and these properties are variously affected in different media. In proportion as the free motion and elastic force of the ether are diminished, the velocity of the etherial vibrations is diminished also, pretty much as the velocity of sound decreases in bodies of feeble elasticity. Of two transparent media, according to this theory that will possess the greater refractive power in which the vibrations are performed the more slowly. If, then, a wave of light strikes perpendicularly on the plane bounding two media, then the direction of the light will not be changed, but merely the velocity; thus, *its velocity will be less in that which has the greater refractive power, and greater in that which has the less.* If the direction in which the wave travels be not perpendicular to the planes bounding the two media where they are in contact, it is evident that one portion of the wave will enter the second medium before the other portion. If the ether become less elastic in this second medium, that portion of the wave which entered first vibrates less rapidly, and the wave is inclined so that the direction in which it is propagated approaches towards the perpendicular. On the contrary, if the ether be more elastic in the second medium, the velocity of that portion of the wave which first enters is increased, whilst the remaining part continues to move at its original rate, and the wave becomes bent towards the plane of incidence.

Fig. 38.



To render these explanations more clear, imagine the waves of light to come from a very remote point *a*, *fig.* 38, so that small portions of the wave, though really arcs of an immensely large circle, may practically be regarded as straight lines, and may be represented as such A B, A′ B′, A^2 B^2. We will now consider only A′ B′, on the particle *b* arriving at *m n*, the boundary of the second medium, the velocity of the wave becomes altered; if the medium be one of higher refractive power, the velocity of the light will be diminished, so that in the same time as it would have passed over the distance *b f* in the former medium, it will only traverse the shorter space *b t*. Meanwhile, however, another particle *p* of the same wave A′ B′, which moved in the upper medium, and consequently retained its original velocity, will have accomplished the distance *p g*, its path being both parallel to *bf*, and equal to it. In the same time that part of the wave which has entered the denser medium is in the position *etg*, and what is true of this particular wave holds equally good of the others. It must be observed that the direction in which the undulation is propagated in the lower medium, is not the same as the direction *a b* in which it moved at first; for the perpendicular to *e t g* is *b c*, whence the ray *b c* is refracted towards the perpendicular. If, on the contrary, the lower medium have the less refractive power, then the wave of light enters into a more elastic ether, and its velocity becomes greater. The particle *b* of the wave A′ B′, *fig*, 38, performs the distance *b t*, whilst the particle *p* in the upper medium traverses only the space *p g*; in this case the wave acquires the position *etg*, and *b c* is the perpendicular to it, which marks the direction in which it advances, consequently the ray *b c* is refracted from the perpendicular.

A. *Refraction of Light in Media having Plane Surfaces for their Boundaries.*

§ 302.

Parallel rays which fall upon a plane refracting surface, as *a b*, *a′ b′*, *fig*. 39, continue parallel after refraction, as *b c* *b′ c′*, because the angle of refraction X is of equal magnitude in each. But if

Fig. 39.

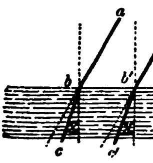
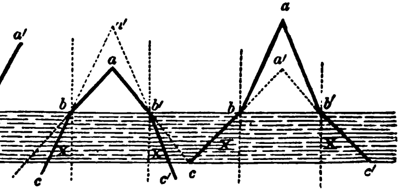


Fig. 40.



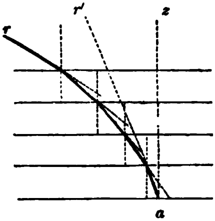
divergent rays proceed from any point and fall on a plane, they will be less divergent if the medium they enter be of a greater refractive power than that from which they issued, and more divergent if the second medium be of lower refractive power than the former. This will be readily perceived on inspection of *fig*. 40, *a b* and *a b′* being the original rays, and *b c*, *b′ c′* the refracted rays. In the former case they appear to have come from a more, and in the latter from a less, remote point *a′*.

From these considerations we can explain a phenomenon already noticed (§ 299.), that all bodies under water appear to be nearer the surface than they actually are.

§ 303.

If several transparent media are arranged in parallel strata one above another in the order of their refractive powers, the most powerfully refractive medium being the lowest; then a ray of light falling perpendicularly upon them will not have its direction changed; but if a ray come obliquely, it will be drawn more and more towards the vertical line in each successive stratum, as is shown in *fig.* 41. To an eye situated at *a*, the radiant point *r* would not appear in its true situation, but at *r′*, which may be found by drawing a tangent to the curve from *a*.

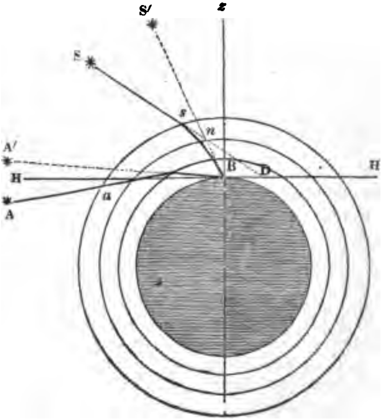
Fig. 41.



Now, as we know (§ 198.), that the strata of our atmosphere are of increasing density as they approach the earth's surface, it follows that every ray of light falling obliquely on the atmosphere, must describe a curve somewhat resembling the above. On this fact depend the phenomena of *astrononomical* and *terrestrial refraction*, as also do those instances of *unusual refraction* that have been observed at different times, and which are known as *Mirage*, *Fata Morgana*, &c.

Astronomical refraction is caused by the rays of light from the heavenly bodies falling upon our atmosphere, in conse-

Fig. 42.



quence of which no stars appear to us in their true places, except such as are exactly in our zenith; all others are more or less elevated, according as they are more or less near to the horizon; nay, they even seem to be above it after they have set. — Let the dark circle in *fig.* 42 represent our earth, and the concentric circles around it various strata of our atmosphere, whose densities decrease as their distance from the earth increases. Suppose an observer to stand at B; then *z* will be his zenith, H B H′ his horizon, S any star, S B *z* its true zenith-distance, and S B H its true altitude above the horizon. But in consequence of the refraction of this star's rays in their passage through our atmosphere, as shown by the broken line S *s* B, it will appear to an observer at B to be at S′, *i. e.* at less than its true distance from the zenith. Produce the original direction of the ray S *s* so that it may cut the apparent ray S′B in *n*; then the angle B *n* D formed by these two lines, is the aberration of the star S, or the refraction of its rays for the apparent zenith-distance *z* B S′, at which it is seen by the observer at B. Tables have been constructed by which for any observed zenith-distance the refraction can be found, which will give the true zenith-distance. The greater this becomes, the greater also is the refraction, until for stars in the horizon it reaches the maximum, when it is about 33′. This *horizontal refraction* has the effect of elevating to or above the horizon such stars as are depressed below it. — Referring still to the same diagram, let A be any star below the horizon B H of an observer at B; on account of the rectilinear propagation of light the star would be invisible, were it not that on the rays A *a* falling on the atmosphere at *a* they become refracted in the curve *a* B, so that the spectator sees the star in the direction of the last tangent to the curve, *i. e.* it will appear to him at the altitude H B A′ above the horizon. — One consequence of this atmospheric refraction is, that the sun rises earlier and sets later than he otherwise would, by which means our day is both advanced and prolonged. In central Europe the longest day is thus lengthened about 8·5 minutes, and in the polar regions the sun's stay above the horizon is lengthened by a month. Again, in sultry weather, in the mornings and evenings the lower strata of air cool rapidly, whilst the upper suffer but a small change in temperature; in consequence of this the discs of the sun and moon appear flattened, so that their horizontal diameter considerably exceeds the vertical; this phenomenon is owing to the fact that the refraction diminishes with the height, the lower portions of these luminaries are consequently more refracted than the upper.

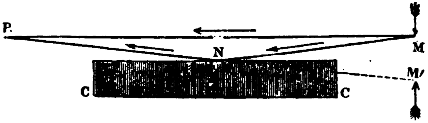
Since refraction affects the position not only of those heavenly bodies which lie beyond the limits of our atmosphere, but as all objects in it are also influenced in like manner, we speak of its operations on them as the effects of ***terrestrial refraction***, one consequence of which is that distant objects (such especially as are in or near the horizon), hills, trees, buildings, &c., seem higher than they really are, and occasionally become visible from an opposite coast, when their great distance and the curvature of the sea's surface prevents their being seen under ordinary circumstances. The difference between this apparent and the true height of any object above the horizon, or the difference between the angles of these two altitudes, is the magnitude of the terrestrial refraction.

Neither astronomical nor terrestrial refraction are always equal, as they depend on the density of the strata composing the atmosphere; and from causes which have been noticed in the earlier part of this work, we know that the density varies. For this reason the measurement of celestial altitudes, as well as that of the heights of terrestrial objects, is greatly embarrassed when considerable nicety is required, and the results obtained are consequently unsatisfactory.

Nearly connected with that property of the atmosphere we have just noticed, is the unusual refraction sometimes called the *Mirage*. In this phenomenon distant objects which ordinarily are not visible, appear to float in the air; and frequently inverted images of them are seen immediately below the spectra of the objects themselves, thus presenting a striking resemblance to the reflection of objects in water. This unusual refraction frequently happens when there intervenes between the spectator and the objects a large expanse of smooth water, as on the Oldenburg coast of the North Sea, where it is called *Kimmung*, or as at the straits of Messina, between Sicily and Italy, where the name of Fata Morgana has been given to the same natural phenomenon. Scoresby has mentioned several instances in which he observed it in his voyages on the coast of Greenland, in 1822. It has been noticed likewise on extensive plains, as the steppes and deserts of Asia and Africa, in which last quarter of the world it was taken notice of frequently by the French army, in Lower Egypt, in 1798-1799. These extraordinary spectacles are not always to be seen; they commonly happen towards evening, after a close and sultry day, when the air is in a calm state, so that the different strata can arrange themselves according to their densities, and when a wind arises the phenomenon ceases. These aërial pictures are supposed to be caused partly by the refraction of the rays of light, and partly by their reflection when they fall upon a stratum much rarer than that through which they first passed. See the 5th Law of Reflection, § 300.

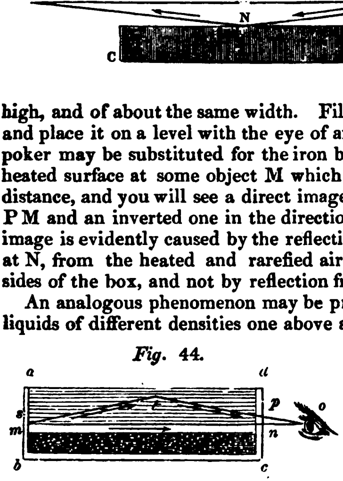
Expt. A result closely resembling the effects of unusual atmospheric refraction, may be obtained thus:—C C, *fig.* 43, is a box of sheet iron, about 30 inches long, 6 or 7 inches high, and of about the same width. Fill it with hot charcoal and place it on a level with the eye of an observer: a red-hot poker may be substituted for the iron box. Look along the heated surface at some object M which is not at too great a distance, and you will see a direct image of it in the direction P M and an inverted one in the direction P M′. The second image is evidently caused by the reflection of the rays of light at N, from the heated and rarefied air that surrounds the sides of the box, and not by reflection from the iron.

Fig. 43.



An analogous phenomenon may be produced by arranging liquids of different densities one above another. Pour some water into a glass vessel *a b c d*, *fig.* 44, to the height *m n*, then add a solution of Glauber's salts, or common salt, which must be carefully poured through a funnel with a very small mouth, and whose end reaches to the bottom of the vessel, so as not to agitate the water. By this means we obtain a fluid whose density decreases upwards. Stick a strip of paper on which a word is printed at *s*; and by looking at *o* on the opposite side, and at an equal height with *s*, the word will be seen in its natural position, by means of the ray *o s*; and again an inverted image of it will be visible in the direction *o t* in the higher and rarer stratum of fluid, in consequence of the reflection of the oblique ray *s t*.

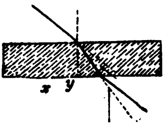
Fig. 44.



§ 304.

When a ray of light passes through a medium bounded by parallel superficies, as *e. g.* a plate of glass, and surrounded by a uniform medium of less density, as air, then *the direction of the incident ray is parallel to that of the emerging ray*, and we consequently see all objects viewed through such a medium in their natural position; for in whatever degree the light may be deflected towards the perpendicular on its entering the glass, it will be bent just as much from it on its emerging again into the air. If the body through which the ray is transmitted be very thick, and if the light fall very obliquely, there arises a remarkable reflection of the ray, whose direction, however, suffers no change. *Fig.* 45. will make this more plain.

Fig 45.



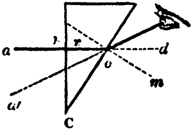
Expt. The direction of the light may be made evident if a ray of sunlight be admitted into a darkened room upon a pretty stout plate of glass or upon a cubical glass vessel filled with water. The ray will describe the path indicated in *fig.* 45.

§ 305.

If the sides of the medium through which the ray is transmitted be inclined at an angle to each other, as is the case in a *prism*, then the ray, on quitting the body, will not be parallel to the incident ray, but will be turned towards the thicker part of the prism (it is assumed that the prism is denser than the ambient medium). An eye placed so as to receive the refracted ray, will not perceive the luminous point itself, but only an image of it, in the direction of the refracted ray produced, and consequently nearer the vertex of the prism than the actual point. The angle which represents the ray's angular change of direction is called the *Angle of Deviation.*

The passage of a refracted ray through a prism may be deduced from the laws of refraction with which we are already acquainted. The simplest case will be that in which the ray is supposed to fall perpendicularly, as *a b*, *fig.* 46, upon the face A C of the prism A B C. Then (by § 299.) this ray is not bent till it arrives at the side B C on which it impinges obliquely at *c*; when it emerges into the air, it will not continue in the direction *c d*, but will be bent from the perpendicular *m c* in the direction *c o*, according to the index of refraction of the surrounding medium. An eye

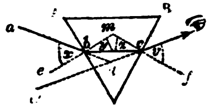
Fig. 46.



at *o* would therefore see the radiant point at *a′* instead of at *a*, and the angle *a c a′* will be the angle of deviation.

In a similar manner we might easily determine the direction a ray must take falling obliquely on the side of a prism, if we knew the index of refraction of the transparent medium. Let A B C be a transverse section of a prism of common glass, *fig.* 47, and let the ray *a b* fall obliquely on A C, then on entering the prism it will be refracted in the direction *b c*, which is found by drawing the perpendicular *e b m*; and from the given angle of incidence *x* we obtain the angle of refraction *y*, the relative refractions of air and glass being 3 : 2 (§ 300.). The ray *b c*, on its emergence into the air at *c*, takes the direction *c o*, which is found by drawing the perpendicular *f c m*, and making the angle of refraction *v*, in due proportion to the angle of incidence *z*; the ratio of the refractions of glass and air, it will be remembered, is as 2 : 3; the angle *c d b* is the angle of deviation.

Fig. 47.



Expt. Admit a ray of sun-light into a darkened room so that it may fall perpendicularly on the side of a glass prism, as *a b*, *fig.* 46, and the ray will be seen to take the direction indicated in the diagram by the line *a c o*. If the light fall obliquely, its path will be that shown by the line *a b c o*, *fig.* 47.

If *a* be a luminous point, as for instance an aperture in a shutter through which a sun-beam is admitted, or if it be the flame of a candle, and a spectator should stand at *o* on the opposite side of the prism, the radiant point will be seen by him, not at *a*, but at *a′*, nearer to the vertex of the prism.

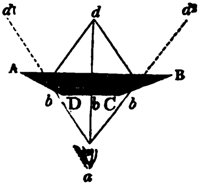
This refraction of light, as well as the change of place undergone by the object, is attended with a remarkable display of colours, of which further notice will be taken presently.

§ 306.

If a transparent body have many faces, the rays of light transmitted through it will take different directions, according to the inclination of these faces. An eye in which such a pencil of rays meets, will see the object repeated as many times as the polyedron has sides; hence the name of *Multiplying Glasses* given to glasses of this construction.

Let *fig.* 48, A B C D, represent such a glass, having three faces. The rays *d b* from a luminous object at *d* will be refracted in passing through the glass, so that an eye placed at *a*, where they meet, would see three images; one direct at *d*, and two by refraction at d^1, d^2.

Fig. 48.



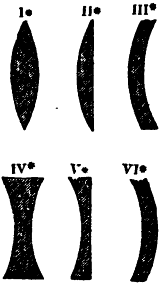
The *Dioptric Anamorphoses* depend on this species of refraction. They are pictures which, when viewed through a kind of multiplying glass, present to the eye images very unlike the pictures themselves.

B. *Refraction in Glasses having Curved Surfaces, i. e. in Lenses.*

§ 307.

Glasses, one or both of whose surfaces are spherical, *i. e.* which constitute segments of spheres, are termed *Lenses:* they are of two principal kinds, *convex* and *concave*, *fig.* 49. Convex lenses have either both sides convex, I*, and are termed *double-convex;* or they have one side plane and the other convex, II*, *plano-convex;* or one side convex and the other concave, III* (such that the two surfaces, if continued, would meet), and are called *menisci.* Concave lenses are either, IV*, *double-convex;* or V*, *plano-concave;* or VI*, *concavo-convex*, the concavity exceeding the convexity.

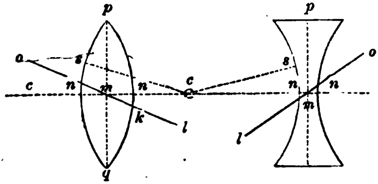
Fig. 49.



Lenses III* and VI* are termed *periscopic* lenses; when their concave and convex surfaces are equal, they act as plane glasses.

Lenses are usually made of glass, but sometimes, for various purposes, of polished rock crystals and precious stones. Hollow glasses, whose intervening space is filled with some fluid of high refracting power, are sometimes substituted for lenses of solid glass.

Fig. 50.



The point *c*, *fig.* 50, is called the *geometric centre* or *centre of curvature* of a lens; *p q* is the *diameter* or *linear aperture;* and *m*, its middle point, is the *optical centre;* a straight line drawn through *m*, at right angles to the diameter, is termed the *axis* (*p* and *q* are the *vertices* of the lens). Radii, as *c n*, *c s*, being at right angles to the curved surfaces, constitute *perpendiculars* for every point of incidence of a ray of light. A *principal ray* is one which passes through the optical centre, as *l m o*.

§ 308.

If we conceive planes to be so placed as to touch all the lenses at the points *n n*, it is evident that such planes must be at right angles to the axes, and consequently parallel to each other; but if planes touch the surface of a lens at any other two points either above or below the axis, such planes will cut each other, and their angle of intersection will be greater as their points of contact approach the rim of the lens. Hence all lenses in the refraction of light act like prisms formed by the two touching planes, which we have imagined to be placed on the surface of the glass at the points of a ray's incidence and emergence. They therefore resemble a combination of an infinite number of prisms with varying angles of refraction, or multiplying glasses with an infinite number of refracting surfaces. Since every ray of light which passes through a prism, is refracted towards the thicker part (§ 305.) of the prism, it follows that convex lenses will refract rays towards the axis, and concave lenses will refract them from the axis.

§ 309.

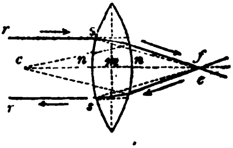
After the explanation just given as to the general principle on which lenses act, we shall be able easily to determine, by means of the laws of refraction (§ 300.), what path a ray will pursue on its emergence from the glass.

Convex lenses refract the rays of light in the following different ways:—

1.) A ray of light falling on a convex glass in the direction of its axis, passes through without suffering refraction; because it is perpendicular to the surface, both on entering the lens and on emerging from it. Likewise every principal ray *l k m n o*, *fig.* 50, is transmitted without any change of its direction, unless the thickness of the glass be considerable.

2.) All rays parallel to the axis will be refracted so that on quitting the surface of the lens, they will converge until they at length cut the axis. If these rays are near the axis, as *r s*, *fig.* 51, they will meet after refraction in the point *f*, which is called the *focus* of the lens. Its distance *f n* from the surface of the glass, or *f m* from the optical centre, is termed the *focal distance;* the focus of parallel rays is known as the *principal focus*, and its distance as the *principal focal distance.* In double convex glasses it is equal to the radius of the spherical surface; in plano-convex glasses it is equal to the diameter.

Fig. 51.



The focus may be found practically by means of the sun's rays.

Those rays which are incident to the glass at a distance from the axis, intersect such as fall upon it nearer to the axis; and, being refracted to a focus less remote than the principal one, they generate both an *indistinctness of the focus* and also the *caustic lines* or *curves.* To counteract these effects of *spherical aberration*, as it is called, the rims of lenses, and sometimes a part of their surfaces too, are covered with rings of some non-transparent substance; so that the rays which pass through the *aperture*, may lie so near the axis as to meet, after refraction, pretty accurately in one point.

First Expt. The refraction of parallel rays can be most clearly shown, by adopting the method described in the first experiment (§ 293.) with a concave mirror.

Second Expt. The caustic curves may be distinctly seen by filling a cylindrical glass vessel with water, and placing it on a sheet of white paper, the rays of light being made to pass through the fluid.

NOTE. § 309. 2.) It is assumed in the text, that the lens is *equally* convex: if, however, this is not the case, put r and r' for the radii of the surfaces, and f for the focal distance, then $f = \frac{2rr'}{r \times r}$. If the plane side is exposed to parallel rays, it is true of a plano-convex glass that $f = 2r$; but if the other side be exposed, then if $t =$ thickness of the lens, $f = 2r - \frac{2t}{3}$.

3.) All divergent rays from the principal focus of a convex lens falling on the surface of the glass and near to the axis will, after refraction, continue their course parallel to the axis, and will therefore never meet.

This direction of the rays will be evident on inspection of *fig.* 51, if it be merely assumed that they proceed from the focus *f.*

4.) Divergent rays which come from a point in the axis more remote than the principal focus, as *e. g.*, *r s*, *fig.* 52, will, after refraction, converge beyond the lens. They will, therefore, at length meet in a point *r′* in the axis, whose distance from the lens exceeds the principal focal distance; and this point will be more remote the nearer the radiant point is to the focus.

Fig. 52. *a.* shows the direction of the rays.

Fig. 52. *a.*

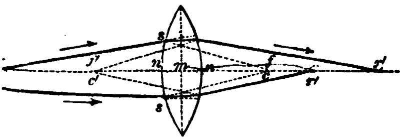
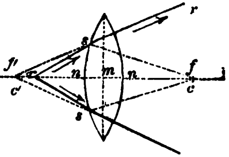


Fig. 52. *b.*



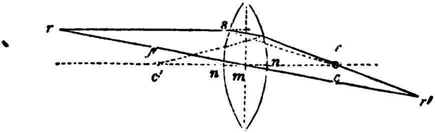
5.) Lastly, rays which come from any point in the axis nearer to the surface of the lens than the focus, diverge more widely than such as proceed from the focus. They will, therefore, be so refracted as to continue divergent after emergence from the lens.

The direction of such rays is depicted in *fig.* 52. *b.*

§ 310.

The image of any luminous point whose rays are refracted by a convex lens, is formed at the point of these rays' intersection. If we find where two rays that pass through the lens intersect, we shall thereby determine the position of the image. Of the infinite number of rays which, issuing from a single point, are transmitted through such a glass, there are two that will be found the most convenient to employ; *viz.* one principal ray, which, if the lens be not of excessive thickness, will pass through the optical centre and proceed without suffering any change in its direction; and one ray parallel to the axis, such that, after refraction, it will go through the focus. The point of intersection of these two rays determines the position of the image of the radiant point.

Fig. 53.



To determine the position of the image of the radiant point *r*, *fig.* 53, draw *r s* parallel to the axis; this ray, when refracted, will pass through the focus *f* in the direction *f r'*; draw another ray, which shall be transmitted so as to pass through the optical centre *m*, and persevere unchanged in its direction to *r'*; this, their point of intersection, is the image of *r*.

The image of any radiant point in the axis of a lens will also be in the axis; and the image of a point on one side of this line, will be found on the opposite side of it.

To determine the position of the image of any object whose rays are refracted through a convex-glass, find the images of a succession of points composing the boundary lines of its figure.

§ 311.

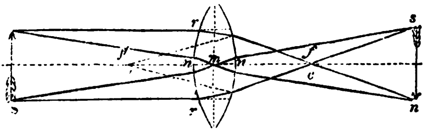
The following phenomena will be produced by the refraction of rays of light through convex lenses, agreeably to the laws explained in the last § but one.

1.) All objects at a greater than its focal distance from a convex lens, produce on the opposite side of the glass an inverted image floating in the air, hence called an *aërial image.*

2.) If the object be very remote, as the sun, an extremely small inverted image of it will be seen near the focus of the lens.

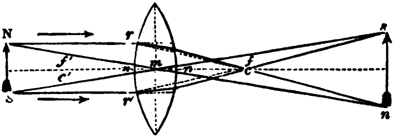
3.) If the object be brought nearer to the focus, its inverted image recedes further from the glass and becomes gradually larger.

Fig. 54.



4.) If the distance of an object from the surface of a lens be equal to twice its focal distance, the aërial image will be at a similar distance on the other side of the lens and of the same size as the object itself. See *fig.* 54.

Fig. 55.



5.) If the distance of the object from the focus be diminished, its aërial image will recede from the glass, and its dimensions will exceed those of the object. See *fig.* 55.

These images, like those reflected from concave mirrors (§ 295.), may be received on any white ground.

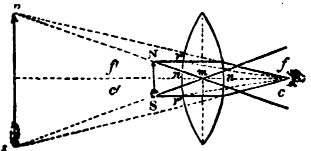
Application of these images in many optical instruments, as in the Camera obscura, the compound microscope, the refracting astronomical telescope. For detailed explanations see below §§ 350.—355.

6.) If any radiant body, as the flame of an Argand lamp or a red-hot coal, be placed in the focus of a convex lens, no image of the object will be produced, but the whole surface of the glass will be rendered luminous; because, by 3. § 309., all the rays which are transmitted through the lens, are parallel to its axis.

In consequence of this property of convex lenses, they are used in microscopes and other instruments to increase the intensity of light.

7.) Lastly, if an object be situated between the focus and the surface of the lens, as N S, *fig.* 56, there will be seen on the same side of the lens with the object itself, an erect magnified image, *n s*, of it, whose distance from the glass is inversely as the distance of the object from the focus. In this case the rays which are refracted through the lens diverge, agreeably to what has been observed in § 309., and intersect, as at *n* and *s*, on the same side of the lens as the object is situated on; to a spectator they seem as if they actually proceeded from these points of intersection.

Fig. 56.



Convex lenses are called *magnifying glasses*, in consequence of their increasing the apparent size of objects viewed at a small distance through them: they are also termed *burning glasses*, because when the sun's rays are brought to a point, after passing through a lens of this kind, they produce a strong heat.

If the phenomena which have been just explained above be compared with those produced by concave mirrors, § 295., it will be found that precisely the same effects follow the refraction of light through convex lenses, as attended its reflection from concave mirrors.

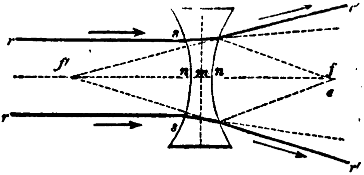
§ 312.

In the refraction of rays through *concave lenses*, we observe that—

1.) A ray falling on the lens, in the direction of its axis, passes through without suffering refraction; every principal ray, also, continues its course without changing its direction. Compare § 307. and *fig.* 50.

2.) The direction of all other rays is changed by refraction; and after emergence from the lens, their divergence increases.

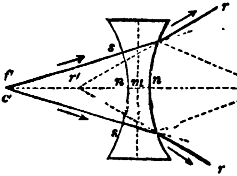
Fig. 57.



3.) Rays near to the axis, and parallel to it, diverge after refraction, and appear, if produced, to come from a *virtual focus*, as is shown in *fig*. 57.

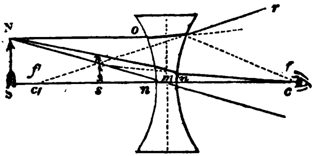
4.) Divergent rays from any point in the axis, diverge still more widely after refraction, and seem as if they came from a point nearer to the surface of the lens than that from which they actually proceed; in *fig.* 58, the rays from f' are refracted towards r, and appear to have proceeded from r'.

Fig. 58.



5.) As concave lenses do not bring the rays which they refract to a focus on the opposite side to that on which the object stands, it follows that they do not present us with any aërial images of objects, but that we see the objects themselves through lenses of this kind, as geometric images, on the further side of the glass. These images are erect, they are invariably less than the objects themselves, and are apparently nearer to the glass. See *fig.* 59. The image of very remote objects is extremely small, and is situated in the virtual focus.

Fig. 59.

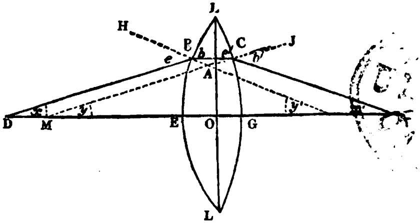


For this reason these lenses are sometimes called *Diminishing Glasses.*

If the reflection of light from convex mirrors (§ 296.) be compared with its refraction through concave lenses, it will be seen that their effects are precisely similar.

[All the phenomena respecting the refraction of light through convex and concave lenses, which we have deduced by construction, agreeably to the universal Law of Reflection (§ 300.), may be inferred and demonstrated geometrically by a process resembling that we have already adopted with regard to spherical mirrors, §§ 295. 296.]

Fig. 60.



Let *fig.* 60, L L represent the section of a convex lens, in the direction of its axis D F; let M be the centre of curvature of the face L G L, and M′ that of L E L.

1.) Let D be any radiant point in the axis, and D B an oblique ray from it: then C F will be the ray after refraction, and O F its focal distance = G F nearly, if the thickness of the lens be inconsiderable.

Now let radius $MG = r$, and $M'E = r'$,

$DE = a$, distance of object from lens,

$FG = \alpha$, distance of image from lens,

H B, a perpendicular to tangent at B.

$\angle DBH=e$, $\angle ABC=b$, $\angle BDM=x$,
$\angle ACB=e'$, $\angle ICF=b'$, $\angle CFM'=x'$,
$\angle AME=y$, and the ratio of refraction between air and water $=n:1$.

$$\text{Then, } \because \sin. e : \sin. b = n : 1,$$
$$\text{and } \sin. b' : \sin. e' = n : 1,$$
$$\therefore \sin. e : \sin. b = \sin. b' : \sin. e',$$
$$\therefore \sin. e + \sin. b' : \sin. b + \sin. e' = \sin. e : \sin. b,$$
$$= n : 1.$$

And if the angles are very small, since the sines of small angles are nearly equal to the angles themselves,

$$\therefore e+b' : b+e' = n : 1.$$

Now $e=x+y'$, $b=x'+y$, and $b+e'=\angle BAM=y+y'$;

$$\therefore x+y'+x'+y : y+y' = n : 1,$$
$$\therefore x+x' : y+y' = n-1 : 1,$$
$$\therefore x+x' = (n-1)y+(n-1)y'. \qquad \text{(A)}$$

And since the angles are very small, we may consider their arcs as right lines perpendicular to the axis D F; then,

$$\tan. x = \frac{BE}{DE} = \frac{BE}{a}; \quad \tan. x' = \frac{CG}{FG} = \frac{CG}{a};$$

$$\tan. y = \frac{CG}{MG} = \frac{CG}{r}; \quad \tan. y' = \frac{BE}{M'E} = \frac{BE}{r}.$$

Also, since the angles are very small, we may substitute in equation (A) the tangents for the angles;

$$\therefore \frac{BE}{a} + \frac{CG}{a} = (n-1)\frac{CG}{r} + (n-1)\frac{BE}{r};$$

and since the thickness of the lens is inconsiderable, $\therefore$ BE = CG nearly; whence from the last equation we have

$$\frac{1}{a} + \frac{1}{a} = \frac{n-1}{r} + \frac{n-1}{r'},$$

$$\therefore \frac{1}{a} = \frac{n-1}{r} + \frac{n-1}{r'} - \frac{1}{a}.$$

Let $a=\infty$, *i. e.* let the rays be parallel:

$$\therefore \frac{1}{a} = \frac{n-1}{r} + \frac{n-1}{r'},$$

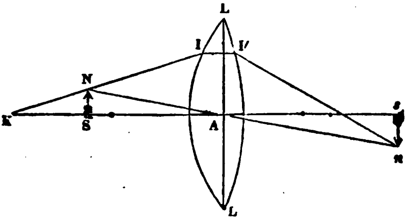
$$\text{or } \frac{1}{f} = \frac{n-1}{r} + \frac{n-1}{r'},$$

NOTE.—In these equations the angles are supposed to be measured by the fraction $\frac{\text{subtending arc}}{\text{radius}}$.

Both these approximate equations are available for all kinds of glasses, observing only that for concave lenses r and r' will invariably be negative. If any one of the 5 magnitudes α, a, n, r, r' is unknown, it may be found by means of these formulæ.

2.) *Let the radiant point* N, *fig.* 61. *be without the axis* As

Fig. 61.



of the lens L L, and let its position be determined by the abscissa A$s = a$, and by the ordinate S N $= b$. If the rays from N make but an inconsiderable angle with the axis, then their focal distance n, may be ascertained by the intersection of the principal ray N A n going through the optical centre A, and the ray incident at I and refracted to I′n. Let abscissa A$s = \alpha$ and its ordinate $sn = \beta$, then its position is accurately determined by the equations: —

$$1.)\ \frac{1}{f} = \frac{n-1}{r} + \frac{n-1}{r'} = \frac{1}{a} + \frac{1}{\alpha}$$

$$2.)\ \beta = \frac{\alpha}{a} \cdot b$$

The proof expressed in words is precisely the same as in § 295.

Now from the foregoing it follows: —

A. For *double-convex lenses*, the radii of whose curvatures are equal, *i. e.* $r = r'$

$$\frac{2(n-1)}{r} = \frac{1}{a} + \frac{1}{\alpha}.$$

and as for common glass $n = \frac{3}{2}$:

$$\frac{1}{r} = \frac{1}{a} + \frac{1}{\alpha}$$

1.) When $a = \infty$, *i. e.* when the object is very remote,

$$\frac{1}{r} = \frac{1}{a}$$

or $a = r = f$

i. e. the *focal distance* is equal to the *radius.*

The physical image of the object is produced in the other focus, it is inverted, and by equation 2.) $\beta = \frac{a}{a} . b$, for it is infinitely small; in this case $\beta = \frac{a}{\infty} . b$

2.) The more a is diminished, *i. e.* the nearer the object is brought to the lens, the less $\frac{1}{a}$ becomes, and consequently the greater a becomes. The inverted physical image is, therefore, further removed from the opposite focus, and magnified.

3.) If $a = r$, *i. e.* if the object be in the geometric centre (in one of the principal foci),

$$\frac{1}{a} = \frac{1}{r} - \frac{1}{r'} = 0$$

$\therefore \ a = \infty$, *i. e.* no image is produced, because the rays emerge parallel to the axis.

4.) When $a < r$, *i. e.* when the object is between the focus and the lens, $\frac{1}{a} > \frac{1}{r}$, $\therefore \ a$ is *negative;* and an erect vertical image is formed on the same side of the lens, such image being more remote and of larger size the nearer the object is brought to the focus; *i. e.*

$$\frac{1}{r} = \frac{1}{a} - \frac{1}{a}$$

B. For *double-concave lenses*, the radii of curvature being similarly expressed, the equation becomes:

$$-\frac{1}{r} = -\frac{1}{a} + \frac{1}{a}$$

1.) If $a = \infty$, then $-\frac{1}{r} = \frac{1}{a}$, $\therefore \ a = -r = -f$; *i. e.* the image is erect, and in the focus on the same side of the lens as the object itself is.

2.) The less a becomes the less also will α be, retaining still the *minus* sign, so that for $a=r$, we have $\alpha = -\frac{r}{2}$; for $a = \frac{r}{2}$ we have $\alpha = -\frac{r}{3}$.

Hence these images will invariably fall on the same side with the object, between the focus and the lens; they are also erect, virtual, and diminished.

C. For *plano-convex lenses*, where $r' = \infty$

$$\frac{n-1}{r} = \frac{1}{a} + \frac{1}{\alpha}$$

and as for glass $n = \frac{3}{2}$

$$\therefore \frac{1}{2r} = \frac{1}{a} + \frac{1}{\alpha}$$

If

1.) $a = \infty$, then $\frac{1}{\alpha} = \frac{1}{2r}$ $\therefore$ $\alpha = 2r = f$.

2.) $a = 2r$, then $\frac{1}{\alpha} = 0$, $\therefore$ $\alpha = \infty$.

3.) $a = r$, then $\frac{1}{\alpha} = -\frac{1}{2r}$, $\therefore$ $\alpha = -2r$.

D. For *plano-convex lenses* the equation is

$$-\frac{1}{2r} = \frac{1}{a} + \frac{1}{\alpha},$$

whence the other values can be found the same as in C.

For *concavo-convex glasses* the equations may be deduced from the preceding, by making the radius r or r' of the concavity negative.]

V. DOUBLE REFRACTION OF LIGHT.

§ 313.

By *double refraction* is meant, that property possessed by many transparent bodies, of dividing into two portions such rays of light as are transmitted through them. Objects viewed through these substances consequently appear double.

This peculiar refraction, however, does not obtain in every direction in which rays may pass through the transparent body;

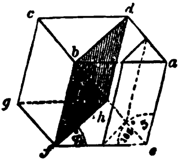
but there are one or two right lines in every such body by which the law of this phenomenon is determined. These lines are termed the *axes of double refraction*, and rays which are transmitted either parallel to one of these axes, or at right angles to it, will not suffer this double refraction, whilst such as pass through in any other direction will be thus affected. Further, the ratio of the refraction of the two divided rays varies in different bodies, and in many it is very small.

§ 314.

Iceland spar is, of all crystallised bodies, the one in which this peculiarity can be most readily observed, because all the natural crystalline faces are so arranged with regard to the axis, that every ray which passes through must necessarily be doubly refracted.

The primitive form of this spar is a *rhomboedron*, or solid bounded by six rhomboids, *fig.* 62. A straight line drawn from one of the obtuse angles *b* of the crystal to its opposite angle *h*, is its *principal axis of double refraction*. If we imagine a plane *b f h d*, to pass through this line, so as to cut the upper and lower faces *a b c d*, *e f g h* of the spar at right angles, this will be the *principal section*. But by § 88. every perfect crystal may be regarded as an aggregate of an infinite number of molecules similar to its primitive form: it follows that every line parallel to this principal axis, will also itself be an axis of double refraction, and a plane passing through it and at right angles to the top and bottom faces of the crystal, will also be a principal section. Lastly, all the faces bounding the crystal through which a ray passes are called *refracting planes*.

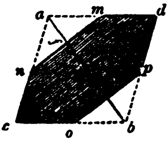
Fig. 62.



The following are the phenomena which may be observed to attend the double refraction of light in calcareous spar: —

1.) If the refracting planes intersect the axis at right-angles, an object viewed vertically through the spar will be seen singly.

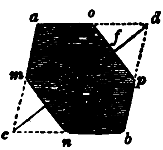
Fig. 63.



First Expt. Prepare a piece of spar, by taking off its obtuse angles in such a manner that the bounding planes may be at right-angles to the axis of double refraction, *i. e.* if *a c b d*, *fig.* 63. were a principal section, and *a b* the axis, then *m n* and *o p* would represent the position of these refracting faces. Every ray falling perpendicularly on them, as, *ex. gr.*, *af*, suffers no double refraction, but passes through as a single ray, in the direction *fb*. Lay one of these faces upon a piece of white paper on which a dot is made, and place the eye vertically over the dot, it will be single.

2.) If the refracting faces be parallel to the principal section or to the axis, an object viewed vertically through the crystal will in this case also appear single.

Fig. 64.

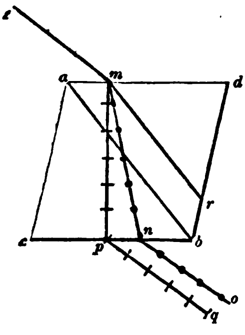


Second Expt. Let *a c b d*, *fig.* 64., represent the principal section of a piece of spar, *a b* will be its axis of double refraction, and *o p* and *m n* will be the faces polished parallel to it. Every ray, as *d f*, falling perpendicularly on them will not be refracted as a double ray, but will continue singly in the direction *f c*. — In this instance a point viewed as in the first experiment will be single.

3.) When the refracting surfaces neither form right-angles with the axis nor are parallel to it, an object viewed through the crystal will appear double. This will be the case when a ray is transmitted through the natural face of the crystal.

A portion of the light is refracted according to the ordinary laws of refraction, but the remaining portion deviates from this course. The former ray is known as the ray of *ordinary* and the latter as that of *extraordinary* refraction.

Fig. 65.



Third Expt. Admit a fine beam of sunlight into a darkened room so that it may be received on a face of Iceland spar: the ray *l m*, *fig.* 65. on entering the crystal will be divided into two rays *m n*, *m p*, which on emerging into the ambient air will be continued in the direction *n o*, *p q*, parallel to each other.

Let *a b c d* again represent the principal section of the crystal, and *a b* its axis: then the refracting faces, *a d*, *a c*, *b c*, *b d*, make with it acute angles, and every ray falling on them is doubly refracted. For instance, let *l m* be a ray of light striking the face *a d* in the point *m*; *m r* would be its axis, and the ray *l m* would be divided at *m* into the two *m n* and *m p*. The line *m n* is the ray of ordinary refraction; its direction is determined from the index of refraction (§ 300.) according to the ordinary laws of refraction, and it is marked by the dotted line. The line *m p*, on the contrary, is the ray of extraordinary refraction, which is inclined farther from the axis than the other, and is distinguishable from it in the diagram by its having little transverse lines drawn across it. — In calcareous spar the angle *n m p* formed by the divergence of these two rays is 6° 12′ when the ray impinges perpendicularly on the crystal. — On emerging from the face *b c*, both the rays suffer a second refraction, and as the two refracting faces *a d*, *c b* are parallel to each other, they continue in a direction parallel to the incident ray *l m*, and to each other, as *p q* and *n o*.

Fourth Expt. Lay a piece of Iceland spar with its natural face over a black point printed or written upon a piece of white paper; the point will be seen double in whatever position the crystal may be placed.

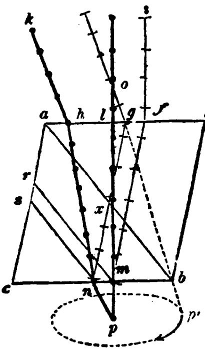
If we look vertically down upon the crystal, both points will be in the diagonal of the obtuse angle, or in the line of the principal section. The point which is nearer to the acute angle of the upper face of the crystal is seen there in consequence of the extraordinary refraction.

If the crystal be turned round over the point whilst the eye is steadily fixed in the same position, the image formed by the extraordinary refraction moves with the principal section about the image which is formed by the ordinary refraction. — Thus it is easy at any time to determine which is the ray of ordinary and which of extraordinary refraction.

Fifth Expt. Place one of these crystals with the diagonal of its obtuse angle over a straight line, and but one image will be seen, because both the refractions are in the direction of this line, the observer as in the former case looking perpendicularly down on the spar. Turn the crystal, and two lines will be visible, which will recede from one another until the diagonal cuts the line at right angles, when the image of extraordinary refraction will have attained its maximum distance from the image of ordinary refraction. If the revolution of the crystal be continued, the lines will appear to approach till the diagonal of the principal section again coincides with the line.

Fig. 66. will illustrate the production of the double image

Fig. 66.



spoken of in the above experiment. Let *a d b c* represent a principal section, and *a b* its axis. Suppose there to be a point *p*, beneath the face *c b*, observed by an eye above the face *a d* of the crystal. Now if *p m* be a ray striking the face *c b*, on entering the crystal it will be divided into the ray of ordinary refraction *m l*, and the extraordinary ray *m f*, which recedes from the axis *m r*. The emergent rays *l o* and *f i*, which are the continuation of these two refracted rays, are parallel to *p m* and to each other. Again, let *n* be a point near to *m*, and let *p n* be its incident ray: it will also be cleft into the ordinary ray *n h*, and into the extraordinary *n g*, which on emerging from *a d* will continue in the directions *h k* and *g o*, parallel to *p n* and to each other. Since the ray of extraordinary refraction forms with the ordinary ray an angle of a few degrees, it is readily perceived that if the points *m* and *n* are sufficiently near, the ordinary ray *m l o* will be cut by the extraordinary *n g* somewhere between *l* and *m*; let it then be cut in *x*. But as the emergent ray *l o* is parallel to *p m*, and *g o* to *p n*, *l o* and *g o* must intersect each other somewhere beyond *a d*; let them do so in *o*. Now if a spectator stand so that his eye at *o* shall receive these two rays, he will see the point *p* by ordinary refraction in the direction *o l*, and by extraordinary refraction in the direction *o g*, or at *p'*, that is to say, nearer the acute angle *d* of the body. If the crystal be made to revolve about the ordinary ray *o p* which goes perpendicularly through it, then the image *p'* generated by ordinary refraction will move in the same direction as the crystal around *p*.

Of the crystals which possess this property of double refraction, there are many which have only *one axis* of double refraction, as the Iceland spar; others again have *two axes*, which are variously inclined towards each other. To the former class, besides the Iceland spar, there belong rock-crystal, tourmaline, sapphire, ruby, emerald, &c.; to the second class mica, topaz, gypsum, arragonite, nitrate of potash, &c.

In all crystals with only one axis of double refraction, which for the most part coincides also with their axis of figure, the ray of extraordinary refraction obeys the same law as in the Iceland spar; the numerical values of their indices of refraction differ however, and in most other crystals, as *ex. gr.*, in rock-crystal, the axis of double refraction is parallel to the natural face, so those rays of light which pass through these parallel faces do not suffer double refraction. In order to produce this effect plainly, it is necessary by artificial means to make their sides inclined with respect to this axis. This further difference obtains between these bodies—that in some of them the ray of extraordinary refraction is inclined from the axis, and in others towards it, more than the ordinary ray. The former, to which class the Iceland spar and rock crystal belong, are said to have a *negative* axis, the latter, as zirconium, a *positive* axis.

The explanation of this phenomenon afforded by the undulatory theory proceeds on the assumption that the æther suffers an unequal division in the interior of those crystals which have a *principal* axis, and that this effect is somehow connected with the laws which regulate their crystallization. (§ 88.) It can be conceived that the forces of crystallization which act variously in the direction of the axes, so modify the æther contained in the crystals as to cause the vibrations which are parallel to the axis to receive a higher velocity than is attained by such as are at right angles to it. Consequently, the undulations are propagated unequally, and also a division of the ray takes place on its entrance into the new medium, those undulations which are propagated most rapidly having a less index of refraction than such as vibrate more slowly. (§ 301.) The equilibrium of the transverse axes in these crystals is explained by supposing that the vibrations which happen in planes perpendicular to the axis of the crystal all have equal velocities. The law of refraction for these undulations is consequently a constant quantity; those vibrations which occur in a plane perpendicular to the principal axis produce the *ray of ordinary refraction*; but that portion of the vibrations which is parallel to the axis, and subject to another law of refraction, on account of the retarded velocity with which it is propagated, generates the *ray of extraordinary refraction*, and it is easily seen that its direction must of necessity depend on the position of the incident ray.

VI. THE PHENOMENA OF COLOURED LIGHT.

§ 315.

Besides producing the phenomena already noticed, light also excites in us the sensation of various *colours*.

The principal source of light to the inhabitants of the earth is the Sun, whose light is white or colourless, as is that of most of the other heavenly bodies; to this general rule there are however some exceptions. The light of luminous terrestrial bodies, as that of a flame, is seldom pure white or colourless; it is almost always more or less coloured; sometimes indeed it is very strongly so.

All white light, and especially that of the sun, possesses the remarkable property of becoming coloured by various means, but principally by being refracted and reflected. The colours obtained by refraction are termed the *prismatic colours;* those which opaque or non-luminous substances exhibit when they either reflect or transmit white light, are called *natural colours.*

§ 316.

The prismatic colours are produced by transmitting white light, especially that emitted by the sun, through colourless prismatic bodies, as, for instance, through prisms of crown or flint glass. Six of these colours can be plainly distinguished by the human eye, *viz.*, *red*, *orange*, *yellow*, *green*, *blue*, and *violet.*

Every ray of sunlight transmitted through a prism, suffers not merely the ordinary refraction (§ 305.), *i. e.*, it is not merely deflected towards the broad face of the prism, but it is also dispersed in the form of a fan and coloured, the pencil of rays maintaining this direction in the plane of refraction. This phenomenon is called the *dispersion* of light, and the six colours compose the *solar* or *prismatic spectrum.* These colours are invariably found to preserve the same relative positions, namely, the red is always least diverted from the vertex of the prism; next orange, then yellow, green, blue, and last of all violet, which is the most refracted. Light, therefore, of each of these individual colours, possesses a different *refrangibility*, gradually increasing throughout the spectrum from red up to violet.

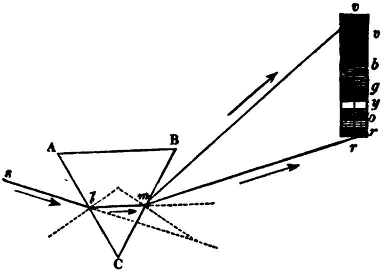
The intensity, also, of these differently-coloured lights varies, that of yellow being the greatest, the strength diminishing towards each extremity of the spectrum.

First Expt. The Solar Spectrum produced by refracting the sun's rays through a prism.

Admit a sun-beam *sl* (*fig.* 67.), through an aperture into a dark room. Receive the ray in the prism A B C, and you will observe,

a.) Instead of the circular image of the sun which would have been produced by the ray, we obtain, by passing the

Fig. 67.



beam through a prism, a stripe of light *r v*, which may be most conveniently received on a white screen, or even upon the wall of the room: the direction of the refracted ray we know from § 305. The ray will also be not merely diverted from its original course, but it will be dispersed or spread out like a fan.

b.) This stripe of light is not white, as was the case with the original ray, but coloured, and in fact the six prismatic colours arranged in the order given above, that is to say, the red is nearest the vertex of the prism, and the violet will be the farthest from it; the former is therefore the least, and the latter the most refracted.

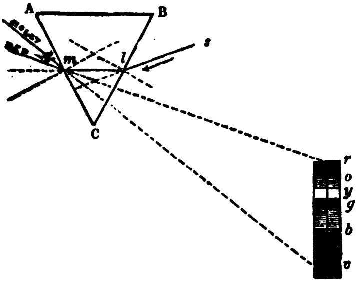
c.) If the screen on which the spectrum is received be brought close to the prism, the space *v r* will be coloured only at its extremities *v* and *r*, the intervening space being white. As the screen is removed to a greater distance, the other colours make their appearance until the intermediate space becomes completely coloured.

d.) If an object be held in the different coloured rays of the spectrum, it will be evidently illuminated most strongly in the yellow light, and the intensity will diminish as it is moved towards the limits of the spectrum. Words written or printed will therefore be read distinctly in yellow light at a greater distance than when held in light of any other colour.

Second Expt. Complementary Spectrum produced when any object is viewed through a prism.

A radiant point seen through a prism is not merely deflected from its position as we have shown (§ 305.), but it appears in the form of a straight line lying in the direction

Fig. 68.



of the plane of refraction; this line is composed of the prismatic colours continuously arranged, but in an inverted order to that which they assumed in the preceding experiment. The violet will now be nearest to the vertex or refracting angle of the prism, and the red will be the farthest from it. It will be seen from *fig*. 68. that this arrangement of the colours must necessarily obtain.

Now if a white screen about two inches in width be the object viewed through the prism, and supposing it to be brought close to the prism, then there will be a column of colour at top and bottom, but all its middle will continue to be white. Increasing the distance of the screen, the next portion to the violet will be changed to blue, and that next to the red will become orange. Removing it still farther from the prism, the coloured portions will increase in width, the white will be completely coloured, and the screen will present a perfect spectrum.

Sir Isaac Newton, who discovered the compound nature of light, by distinguishing the light and dark blue as blue and indigo respectively, made the spectrum to consist of seven colours. If we observe attentively we shall see that the respective colours are not strongly defined, but that the red, by almost imperceptible gradations, is changed into orange, this again, in like manner, is softened off into yellow, the yellow gradually becomes green, the green becomes blue, and this last colour increasing in depth, is at length changed into violet. Hence it has been inferred that the differently coloured rays possess a different degree of refrangibility, increasing from the red to the maximum attained by violet. The coloured stripes in the spectrum are of unequal widths. According to Newton's investigations their respective widths may be expressed by the following numbers, the spectrum itself being assumed as unity:

Red	0·12	Green	0·17
Orange	0·07	Blue	0·28
Yellow	0·13	Violet	0·23

and if the entire length of the spectrum be divided into 360 equal parts, then there will be of

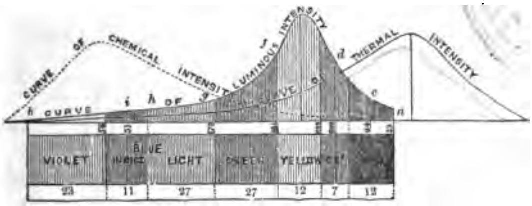
Red,	Orange,	Yellow,	Green,	Blue,	Violet,
45	27	40	60	108	89
56	27	27	46	95	109

such parts, the upper line expressing the relations according to Newton's, and the lower according to Fraunhofer's experiments.

The later and more exact researches of Wollaston and Fraunhofer have shown, that in a perfect solar spectrum the coloured spaces are by no means continuous, but that there are certain interruptions to their continuity, marked by dark lines parallel to the slant edge of the prism. These lines, which are called Fraunhofer's, after their discoverer, are more than 500 in number; they do not follow each other with any degree of regularity, but the same position is always retained in the same kind of light, quite independently of the material of which the prism may be made, or of the size of its refracting angle; in light obtained from different sources, as from the sun and from a lamp, they differ both in number, size, and arrangement; whence it would appear as if every luminous body had a system of light peculiar to itself. These dark lines in the spectrum were used by Fraunhofer for accurately measuring the refraction, the breadths of the individual colours, and the intensity of the light of different luminous bodies. From another set of experiments it has been found, that the dispersive power of different transparent bodies varies, and accordingly, that different kinds of glass produce different distributions of the prismatic colours, as far as regards their respective breadths in the spectrum. Thus, too, the dispersive power of common glass is much increased by the addition of lead to its composition.

In *fig.* 69. is a representation of the solar spectrum, as observed by Fraunhofer with a flint-glass prism, omitting, however, several hundreds of lines. The perpendicular lines in the upper figure from the base line *a b* to the curve *a c d e f g h i b*, express, according to Fraunhofer's measurement, the relative intensities of the light of the different portions of

Fig. 69.



the spectrum immediately beneath. Expressed numerically, the luminous intensity of the extreme red ray is 32, of the middle ray of that colour 94, of orange 640, between yellow and orange 1000, green 480, blue 170, dark blue (indigo) 31, violet from 5 to 6, and, accordingly, the curve representing the intensity of light has been constructed.

The prismatic refraction of the sun-beams by brilliants and other polished gems, as also by the drops of dew and by the rainbow, are matters of common observation. This beautiful arch sometimes appears double, in which case the inner or primary bow exhibits the prismatic colours in such order that the violet is innermost and the red forms its outer boundary; the secondary bow presents these colours both inverted and more feebly. The formation of the rainbow may be explained as follows: let D, *fig* 70., be a drop of rain, and *a b* a ray of light falling upon it, which at *b* becomes refracted as *b c;* at *c* it is reflected in the direction *c d*, and at *d*, its point of emergence, it is refracted a second time, and suffers the prismatic dispersion, when the red ray, as being the least refrangible, takes the lowest direction *d r*, and violet, having the greatest refrangibility, follows the upper path *d v*. In *fig*. 71., let D represent the same drop, and at a certain distance below it let D′ represent another similar drop. The same refraction and production of the prismatic colours will happen in this second drop as in the former, and at some point *o* the red ray of the upper drop will intersect the violet ray of the lower. Suppose a spectator to stand so that his eye shall be at *o*, then from the upper drop he will see red light, from the lower one violet, and from the intervening drops between these two extremes he will receive the intermediate prismatic colours, and consequently between *d* and *d′* he will

Fig. 70.

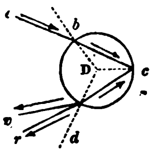
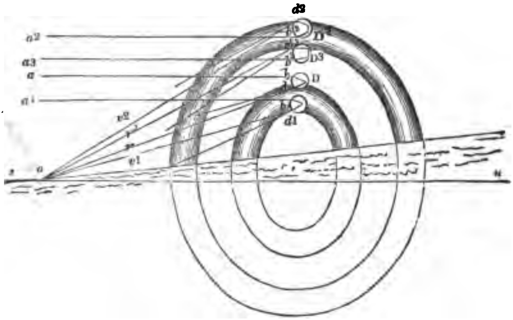


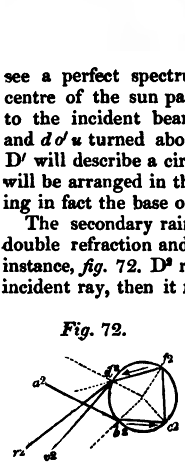
Fig. 71.



see a perfect spectrum. Again, let $s\,u$ be a line from the centre of the sun passing through the eye at o, and parallel to the incident beam $a\,b$. Now imagine the angles $d\,o\,u$ and $d\,o'\,u$ turned about $o\,u$ as an axis, then the drops D and D′ will describe a circle, within which the prismatic colours will be arranged in the order named above; the circle forming in fact the base of a cone whose vertex is at o.

The secondary rainbow may be explained by supposing a double refraction and reflection of the sun's beams. If, for instance, *fig.* 72. D^2 represent a drop of rain, and $a^2 b^2$ be an incident ray, then it receives its first refraction at b^2, its first reflection at c^2, its second at f^2, and lastly, its second refraction and inverted prismatic dispersion at d^2; *viz.*, in this case the violet ray $d^2 v^2$, as being that portion of light which is most strongly refracted, takes the lowest path, and the red ray, $d^2 r^2$, as being the least so, takes the highest; this is clearly the inverse order to what obtained in *fig.* 70. The same holds good with respect to the drops D^2 and D^3, *fig.* 71. Let an eye be placed at o, so as to receive the rays $d^2 v^2$ and $d^3 v^3$ at their point of intersection, then in the drop D^2 it will see the violet ray, in D^3 the red, and in the intervening rays between D^2 and D^3 the other prismatic colours, so that between d^2 and d^3 there will be a complete spectrum, whose lower extremity is red and the upper violet. From the remarks already made about the primary bow, it may be seen how the existence of the secondary arc may be accounted for.

Fig. 72.



Whether a rainbow shall be visible at all, and if so, what portion of its arch depends on the altitude of the sun above the horizon. From accurate observations it has been ascertained, that the angle dou, *fig.* 71. which the red rays in the primary bow make with the axis ou, or with the sun's rays parallel to it, is 42°, and the angle $d'ou$, made by the violet rays with the same, is 40¼°; in the secondary bow, the angle d^3ou of the red rays is 51°, and that of the violet d^2ou is 54°. If the sun be in the horizon, both the rainbows will be semicircles; if he be above the horizon, a portion less than a semicircle will be visible; with an altitude of 42° above the horizon the primary bow vanishes, and at a height of 54° the secondary one also ceases to be visible. A portion greater than a semicircle can be seen only if the observer be so situated as to have the sun below him; thus for instance, if he be on a high mountain, an arc becomes visible proportioned to his elevation; a complete circle of a rainbow may be seen in the spray of a waterfall if a spectator be sufficiently elevated above the horizon. From what has been advanced, it is obvious that each spectator observes his own rainbow, *i. e.*, the phenomenon is produced for each individual in different drops of rain.

§ 317.

If the prismatic colours be made to pass through a second prism, they will be refracted again, and the intensity of each variety of light will be changed, increasing from the red to the violet; but no dispersion will ensue, nor will the colours themselves be altered. The like results will obtain if a luminous point of any single colour be observed through a prism.

Hence the following inferences have been drawn:

1.) Every colour of the solar spectrum contains simple or homogeneous light, and that each colour has a distinct angle of refraction; in other words, there is a difference in the refrangibility of the rays.

2.) That the light of the sun, and, indeed, that all white light, is not homogeneous, but is compounded of the different prismatic rays.

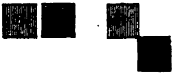
First Expt. Through a small aperture in the screen on which the whole spectrum has been received, allow only a single coloured ray to pass, and let it fall upon a prism; the ray will be bent agreeably to the laws of refraction, but no dispersion of the light will take place, *i. e.*, no oblong spectrum will be produced, nor will the colour be altered.

Further, the red ray will be seen to have the least refrangibility, the orange a greater refrangibility, and so on with each of the other colours, until a maximum is arrived at in the violet.

Second Expt. Admit the light of the sun through three little holes in a shutter placed pretty close to each other and in the same straight line. Before one aperture place a phial containing some pure red liquid; before the second a blue liquid; and look at these three openings through the refracting angle of a prism held horizontally. — The hole through which the white light enters will resemble a line of the prismatic spectrum. Near the red of this spectrum will be seen the aperture by which the red light is admitted; and near the blue of the spectrum will be the aperture of the blue ray: the shape of these openings will be unchanged, but their heights will vary, in consequence of refraction.

Third Expt. Upon a white surface lay a small square of red and blue, R and B, *fig.* 73. (the colours should be as pure as possible); look at them through a prism held with its refracting angle downwards; the two squares will no longer appear side by side, but the blue will seem to be below the red.

Fig. 73.



§ 318.

If all the coloured rays obtained by the dispersion of a sunbeam be combined, white light is produced. — This may be verified by means of the following experiments: —

First Expt. Throw the prismatic spectrum on a convex lens. The rays rendered divergent by the prism, on passing through the lens, will all meet in a focus beyond the glass; at this point they will intersect each other and again diverge. — If the spectrum be received at this point on a white screen, there will be seen a white round image of the sun; but if the screen be removed further from the lens, a spectrum will be obtained similar to the former, but with the colours in inverted order.

Second Expt. Look at a spectrum formed by a prism through another prism similar to the first and parallel to it; the coloured rays will be transmitted in an inverted order through this second prism. — These rays must, on their emergence from the second prism, again be parallel; so there follows no dispersion and no prismatic colouring, but, instead of these, the eye perceives a white image of the sun.

Third Expt. The production of white light from the principal prismatic colours may be thus proved subjectively: on a black screen lay two strips of white paper about two inches wide, so that their sides may be parallel to the refracting angle of a prism held horizontally, and at a distance of from 1 to 1¼ inches from each other. The upper side of the paper next the prism will appear yellow, orange, and red; the lower side of the strip, farther from the prism, will have a green, blue, and violet space. — Bring the strips nearer and nearer to a parallel position with each other, and the halves of the spectrum will gradually cover each other; the coloured spaces will exchange colours, which will become pale and less distinctly marked, till they altogether vanish, on the edges of the paper coming in contact.

In like manner we may obtain white light, by combining only the three prismatic colours—red, yellow, and blue. If only two of these colours be combined, the other three colours of the spectrum will be produced.

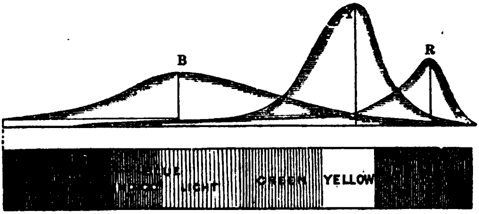
Fourth Expt. Receive a spectrum on a screen in which three holes have been made, so that a red, a yellow, and a blue ray are transmitted. — Let these three be received on a convex lens, and white light will be obtained at the focus on the other side of the glass.

Fifth Expt. Transmit a red and a yellow ray through the screen; combine them by means of a convex lens, and you have orange light: with a yellow and blue, you get green, and with blue and red, violet.

Red, yellow, and blue have hence been termed the *primary* or *fundamental* colours; and the other three — orange, green, and violet — the *secondary* or *compound* colours.

Brewster and several other philosophers are of opinion that white sun-light consists of only these three fundamental colours, and that the other three exist only in consequence of combinations of the former. Sir D. Brewster, in his treatise on Optics (*Cabinet Cyclopædia*, p. 73.), says, "I conclude that the solar spectrum consists of three spectra of equal lengths, viz. a *red* spectrum, a *yellow* spectrum, and a *blue* spectrum. The *primary red* spectrum has its maximum of intensity about the middle of the *red* space in the solar spectrum; the *primary yellow* spectrum has its maximum in the middle of the *yellow* space; and the *primary blue* spectrum has its maximum between the *blue* and the *indigo* space. The two minimum of each of the three primary spectra coincide at the two extremities of the solar spectrum.

Fig. 74.



"From this view of the constitution of the solar spectrum we may draw the following conclusions: —

"1.) *Red*, *yellow*, and *blue* light exist at every point of the solar spectrum.

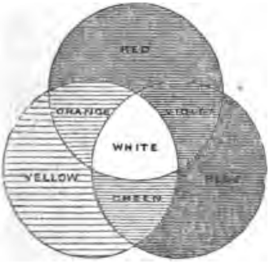
"2.) As a certain portion of *red*, *yellow*, and *blue* constitute *white* light, the colour of every point of the spectrum may be considered as consisting of the predominating colour at any point mixed with white light. In the red space there is more red than is necessary to make white light with the small portions of yellow and blue which exist there; in the yellow space there is more yellow than is necessary to make white light with the red and blue; and in the part of the blue space which appears violet there is more red than yellow; and hence the excess of red forms a violet with the blue.

"——— Now, if we suppose that three parts of yellow, two of red, and one of blue, make white, we shall have the colour at Y (*fig.* 74.) equal to 3 + 2 + 1, equal to six parts of white mixed with 7 parts of yellow; that is, the compound tint at Y will be a bright *yellow*, without any trace of red or blue."— The quantity of red light existing in the orange may perhaps be equal to 4 parts with 5 parts of yellow, and 1 of blue; then, from the preceding explanation, it appears that there remain 2 parts of red and 2 of yellow light which combine to form orange. By similar combinations we may deduce the origin of the other compound colours in the spectrum.

Each of the six prismatic colours has some other called its *complementary* colour, with which, if it be combined, we shall obtain white. The complementary colour to each of the three fundamental colours is the compound colour obtained by mixing the other two fundamental ones; and for each of the compound colours, that primary one which does not enter into its composition.

Fig. 75 will serve, in a simple manner, to illustrate these observations. The three circles which intersect each other, so that the circumference of each passes through the centres of the other two, contain the three primary colours—*red, yellow*, and *blue.* Where two of these spaces come together, we have the secondary colours —*orange, green*, and *violet.* In the middle portion, where the three fundamental colours are combined, we have *white.* The complementary colours are placed in the diagram opposite to each other, surrounding the white light, to represent its reproduction by this combination of colours.

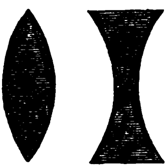
Fig. 75.



§ 319.

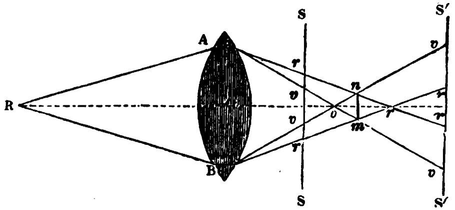
If the figure presented by a transverse section of a lens be attentively considered, it will be seen that the convex lens approximates pretty nearly to what would be formed by placing two prisms, with their bases, one on the other, *fig.* 76. A; and that of the concave lens to the figure made by placing two prisms with their vertices touching each other, *fig.* 76. B, but that in each the angle of refraction is greater towards the edge of the lens.

Fig. 76.



Rays which are transmitted through these glasses must consequently undergo a prismatic dispersion in addition to their ordinary refraction, and this dispersion will be greater the nearer the rays are to the edge of the lens. One consequence is, that objects viewed through them, and images formed by them, are coloured at their edges, by which they lose in distinctness even more than by the spherical aberration of the rays of light. (§ 309.) — The indistinct appearance caused by this prismatic colouring is called the *chromatic aberration* of lenses. It is especially detrimental in the convex glasses (or object glasses) of telescopes, where they are employed for the formation of aërial images of the distant objects which are viewed through the instrument (vid. § 355.).

Fig. 77.



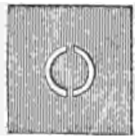
To render this phenomenon, resulting from the course of the sun's rays, more intelligible, let R, *fig.* 77. represent any luminous point; every ray in the pencil A R B proceeding from it is not only refracted, but the pencil is dispersed into the prismatic colours. The most refrangible rays, the violet, meet nearer the glass, at *v*, the red further off, at *r*. Between *v* and *r*, where the greatest number of rays meet, instead of a point, there will be a circle, having a diameter *m n*; this circle is called the circle of aberration.

First Expt. Referring still to *fig.* 77.: intercept the rays which have passed through the convex lens before they arrive at their focus, by placing between the glass and its focus a screen S S of white paper, and on it you will see a circle, white in the middle, around which there will be a belt of yellow, fringed off towards the edge into red. — In this position of the paper, the red being outermost, bound the figure.

Next, place the paper beyond the focus at S′ S′, and the outermost circle will be violet, shaded off into blue, with white in the middle. — In this case, as *fig.* 77. shows, the bounding zone consists of violet rays.

Second Expt. To procure the coloured rings described in the preceding experiment perfectly distinct and free from the interior white space, cut a ring-shaped hole in a piece of thin card-board or tin, as is shown in *fig.* 78. such that its diameter may be rather less than that of the lens's circle of aberration *m n*, *fig.* 77. Hold this screen at the focus, so that the circle of aberration may fall exactly on the space within the ring; this space will receive all the light, so that no rays will be transmitted through the aperture. If the screen be moved in the direction of the axis of the lens, the red will first be distinctly perceived behind it; next, a yellow ring;

Fig. 78.



and, last of all, a white one, if a second sheet of paper be held beyond that in which the aperture is. In like manner, if the plane be removed beyond the focus, a violet ring will first be visible; next, a blue; and then a white one, as before. — The mode in which these rings are produced is clear from *fig.* 77.

§ 320.

It was an object of considerable importance to discover some means by which this indistinctness of the images, owing to the the chromatic aberration of the lenses, might be counteracted. The problem to be solved was therefore, just this, to produce a refraction of the rays of light, which should be unaccompanied with prismatic dispersion. This desirable object was attained by using two substances, which, with nearly equal refractive powers, had very dissimilar dispersive powers. The substances employed were *crown-glass* and *flint-glass.* A prism of the latter kind of glass possesses a much higher dispersive power than a similar prism of crown-glass, but the refraction of the rays is nearly the same in both. Hence it becomes practicable to construct *achromatic* or *colourless prisms* and *lenses.*

Crown-glass is made of flint and alkali only, oxide of lead enters into the composition of *flint-glass.*

According to Dolland's observations, the mean refractive power of flint-glass is to that of crown-glass as 158 : 153; according to Fraunhofer's, 164 : 153 (vid. § 300.); the prismatic dispersion in English flint-glass is 1½ times, but in Fraunhofer's it is twice as great as in crown-glass.

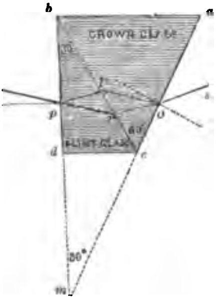
§ 321.

An *achromatic prism* is one through which objects are viewed refracted indeed, so that they are not seen in their true position, but yet free from a prismatic fringe about their edges. They consist of two prisms fitted together, the one being of flint and the other of crown-glass. The vertical angle of the flint-glass prism must be less than that of the crown-glass, and their sizes must be inversely as their dispersive powers.

In English flint-glass the vertical angle of the flint-glass prism must be ⅔ that of the crown-glass, but in Fraunhofer's it must be ½ the size.

These prisms are to be so placed that their refracting angles may be in contrary directions to each other: then, since these angles are not equal, these prisms form a solid, whose sides are not parallel; this is evident from *fig.* 79., where *a b c* is the crown-glass, and *b c d* the flint glass, prism. Produce the converging sides of the trapezoid *a b c d*, formed by these two prisms, and the prismatic form *a b m* is restored, its vertical angle *m* being equal to the difference of the vertical angles of the two prisms composing it. In an instrument constructed in these exact proportions, the prismatic dispersion *v r* of the ray *s o*, produced by the crown-glass prism, is refracted back in the contrary direction *v p*, *r p*, and is thus counteracted, the rays on their emergence at *p* reuniting and continuing parallel to the refraction expressed by the angle *a m b*.

Fig. 79.



Strictly speaking, a perfectly achromatic prism has no existence, because the dispersive power of the transparent medium is not the same for all the coloured rays; consequently, by means of two prisms, we can make a compound one achromatic only with respect to two colours, commonly the two extremes red and violet are selected.

§ 322.

Lenses are rendered achromatic on precisely the same principles as prisms; they, too, are compounded of crown and flint-glass, and commonly a convex lens of the former is combined with a concave lens of the latter glass. *Fig.* 80. is a sectional representation of such a lens; the refracting angles *x* and *y* must be inversely as the dispersive powers of the respective glasses. Lenses of this kind act like convex lenses, but they are free from prismatic dispersion, whence the images they produce are perfectly distinct, and free from colour about their edges.

Fig. 80.

Newton believed that it was an impossibility to obtain an achromatic glass; Euler inferred from the construction of the eye that it might be made; and Dollond, in 1757, was the first who actually succeeded in making prisms and lenses possessing this property. In later times Fraunhofer has attained a high degree of perfection in the construction of his glasses.

§ 323.

The colours in which non-luminous objects appear to us, called *natural colours*, are not any thing peculiar to the bodies themselves, but are produced merely by the white light which falls upon them, or which is transmitted through them, being in part absorbed and in part decomposed.

In opaque bodies these colours result from the reflection and change of the white light, which is incident on their surfaces. Such objects as throw back the white light unchanged, themselves appear *white*; such as absorb almost all the light that falls upon them are *black*; such as reflect but a part of the white light from their surface give rise to the many gradations of white and black, known as the various shades of *grey*. Those objects, on the contrary, which decompose the white light they receive and absorb some portion of it, appear to us of that particular colour which is obtained by combining the coloured rays they reflect; red bodies, therefore, reflect none but red rays, blue ones blue rays, and so on; those substances which reflect more than one coloured kind of ray are of some one of the secondary colours; lastly, as from many points of their surface white light is reflected, whilst from others there is no reflection whatever, we may understand how the infinite shades of colour originate.

That these natural colours are really the effect of white light, and that they are not innate properties peculiar to the bodies themselves, is clear from the fact, that when placed in simple homogeneous light, which admits of no decomposition, all bodies, whether white or coloured, appear of the same colour with the ray that falls upon them; indeed, they seem most strongly coloured when placed in light like that which they peculiarly reflect, but all other colours are more or less absorbed by them, so the perfect blackness of black bodies becomes more or less dimmed by exposing them to the prismatic rays of the spectrum.

Test the accuracy of the above remarks by holding articles of different colours in the various lights of the solar spectrum.—Yellow tinge observable in bodies illuminated by the homogeneous yellow light of a spirit lamp, produced by common salt.—Articles of furniture in a room coloured by making the day-light pass through stained glass or painted blinds.—The flames of our artificial sources of light shed a yellowish light, inclining sometimes even to orange, as may be very plainly seen by noticing them during the daytime. Hence it is that we find it difficult by any kind of artificial light to distinguish accurately the colours of bodies, and especially so if they be blue or green.

Transparent bodies exhibit similar phenomena. They appear either colourless if they transmit white light unchanged, or else they seem coloured if they decompose it. In the latter case they either reflect the same light as they transmit, or the transmitted light is of a different colour from the reflected.

The different sorts of stained glass and many kinds of liquids may serve to show the truth of the preceding explanation. — Thus a solution of lac reflects blue light and transmits red; a solution of chromate of alum looks green in reflected light, but reddish purple in transmitted light. — The blue tint of the atmosphere in reflected light, and its red tinge in the morning and evening in consequence of the transmitted rays of the sun. — The sun when seen through a dense fog looks pale like the moon. — Smoke when illuminated by the sun's rays has a bluish tinge; the sun if seen through smoke is reddish.

§ 324.

Dyes and Paints are substances which when applied to bodies so change their surfaces that when seen in white light they reflect only the peculiar colour of the dye or paint. The fundamental colours from a mixture of which we obtain an endless variety of tints are — white, red, yellow, blue, and black.

White light may be reproduced by a mixture of natural colours in the same manner as we have already shown it may be procured by a combination of the prismatic colours; the only requisite is that they shall be moved so quickly that the eye receives the impression of all the colours simultaneously.

First Expt. Procure a solid wheel to which by some mechanical appliance a rapid motion may be communicated, and cover it with pieces of paper or parchment painted with the prismatic colours as pure as possible: the paper should be cut in the shape of the sectors of a circle, and the arcs should be proportional to the lengths of the colours in the solar spectrum as given in § 316. — If the proportions of the colours be correctly observed, and if the colours themselves are pure, the rapid rotation will produce white, or at least a colour almost white.

Second Expt. If the circle be divided into three sectors of 120° each, and these be coloured with the fundamental colours, red, yellow, and blue, we shall in this case produce the impression of white light by turning the wheel rapidly as in the first experiment.

Third Expt. Cover two thirds of the circular plate with one of the secondary colours, orange, green, or violet, and the other third with its complementary colour blue, red, or yellow, and with the same proviso as in the other experiments as to the purity of the colours, a rapid rotation will give white, or a colour approaching very nearly to white.

Fourth Expt. Cover one half of the plate with one of the primary colours and the other half with another such colour, on turning the plate quickly it will seem as if it had been covered all over with that compound colour which is produced by the mixture of the two particular primary colours you have employed: thus, *ex. gr.*, if one half be red and one yellow, the whole will appear orange; if half red and half blue, violet; if half blue and half yellow, green.

Fifth Expt. If the fundamental colours are not applied in their due proportions to form white light, then the plate on turning round will appear entirely of that colour which is in excess, or of the compound colour which is produced by any two of them which may be in excess. — Thus if one semicircle be red, and two quadrants blue and yellow respectively, then the whole seems of a bright red. In its rotation only so much of the red combines with the blue and yellow as suffices for the production of white, and the excess tinges the white thus generated of a red colour. — This experiment goes far towards proving the accuracy of Brewster's hypothesis given in § 318.

The preparation of these coloured plates is not so extremely easy as might be supposed; besides the perfect purity of the colours employed, it is also necessary to ensure that they shall not be laid on too thickly or too dark, as the colours resulting from the rotation of the wheel will then be more or less indistinct. The effect is rendered more striking and complete by bounding the colours in the centre and at the periphery with a black band about ½ an inch in width.

§ 325.

The different chromatic phenomena which we have just described are accounted for in the following manner, according to the two principal theories which have obtained with regard to the nature of light.

The corpuscular theory assumes the existence of various kinds of luminous matter, each of which excites in our eyes the sensation of some particular colour. By the combination of two or more of these, the sensation of a compound colour is excited, and when particles of all the different varieties come in contact with our organs of vision we see white. A white ray, according to this hypothesis, would be one containing portions of all the species of light.

The dispersion of light into the colours of the spectrum, consequent upon its refraction through a prism, is explained by supposing that transparent bodies attract the different sorts of light unequally; their refraction is therefore unequal; and thus, on their emergence from the refracting medium, the rays become dispersed.

In like manner the existence of natural colours is explained by saying that the coloured bodies absorb one or more of these varieties of light and reflect the others. White bodies are supposed to throw back all the rays; black, on the contrary, absorb all; red reflect none but the red rays, and retain those of all the other colours, &c.

According to the undulatory theory the production of coloured light is supposed to be owing to the different velocities with which the particles of æther vibrate; and thus a distinct sensation is excited in the eye analogous to that which is experienced by the ear from the different velocities with which the undulations of the atmosphere are propagated. As high and low notes result from the different velocities of these aërial undulations, so the different colours owe their origin to the unequal velocities with which the æther vibrates. Thus red light is supposed to be caused by the æther performing about half as many vibrations as are requisite to form violet; the waves of red light are therefore double the length of the violet waves, since they are all propagated with equal velocities.

From their observations on the interference and curvature of the waves of light, Fraunhofer, Herschel, and Fresnel have deduced the lengths of the waves of the prismatic colours to be as follows:

	Ten thousandth parts of a millimetre.		
	Fraunhofer.	*Herschel.*	*Fresnel.*
For the extreme red light	7·400	6·756	
red	6·879	6·502	6·20
orange	6·559	6·096	5·83
yellow	5·888	5·766	5·51
green	5·265	5·613	5·12
blue	4·856	4·978	4·75
indigo	4·296	5·699	4·49
violet	3·963	4·420	4·23
extreme violet		4·242	

NOTE. — The above calculations have not been reduced to English measures, the French decimal scale being so much more convenient for estimating minute quantities. — It may be added that 1 metre = 39·371 English inches, consequently 1 millimetre = ·039371 of an inch.

Hence it follows, as we have remarked already, that the waves of red light are the longest, and those of violet light are the least; the former indeed (at least according to Fraunhofer's estimate) are almost exactly twice the length of the latter; red light will therefore perform only half as many vibrations in a given time as violet.

Since according to Fraunhofer a wave of the extreme red light is 0·00074 of a millimetre long, and a wave of violet is 0·00039 of a millimetre, it is clear that 100,000 waves of the former occupy the space of 74^{mm}, or that 1,351,351 go to a metre: of the latter light there will be 100,000 waves in 39^{mm}, or 2,564,102 will go to a metre. As we know the number of miles light travels in one second (§ 286.), it may be found that red light excites in that space of time nearly 421 billions of waves in the æther, and that in the same time violet lights excites about 799 billions of waves.

If the number of vibrations made by coloured light be compared with those performed by sonorous bodies, it will be seen that whilst in the one case the lowest note makes 16 entire vibrations or 32 excursions in a second (§ 238.), red light, which is the lowest note in the scale of colours, accomplishes about 29 billion times as many vibrations. Again, all the notes which are audible by our ears are comprised within the range of 9 octaves, and all the colours appreciable by our organs of sight range nearly within a single octave. If our organs of vision were more exact, probably a greater variety of colours might be distinguished.

If with Sir Isaac Newton we allow indigo a place in the spectrum as a distinct colour, we shall render the analogy between the prismatic colours and the notes in an octave (§ 238.) still more striking. To render the comparison more obvious, the prismatic colours are arranged immediately under the notes of the gamut: —

1.	2.	3.	4.	5.	6.	7.
c.	*d.*	*e.*	*f.*	*g.*	*a.*	*b.*
Red,	Orange,	Yellow,	Green,	Blue,	Indigo,	Violet.

When several musical notes are sounded together they produce either a chord or a discord, of which our ear is sensible; so by the simultaneous action of two or more waves of light, propagated with different velocities, the sensation of a compound colour is produced; and when the waves of all the simple colours act together, the sensation of white light is excited.

The different refrangibility of light, and the prismatic dispersion consequent upon it, admits of being easily explained; for a wave that vibrates with a higher velocity than another will suffer a different refraction from that suffered by the latter, if the two waves be transmitted through the same medium, as, *ex. gr.*, through glass. (§ 301.)

Lastly, as regards the colours generated by the reflection of light; it may be seen how it is possible that the velocity of the incident wave may sustain a different modification from different bodies, in consequence of which modification of velocity different substances will be of different colours.

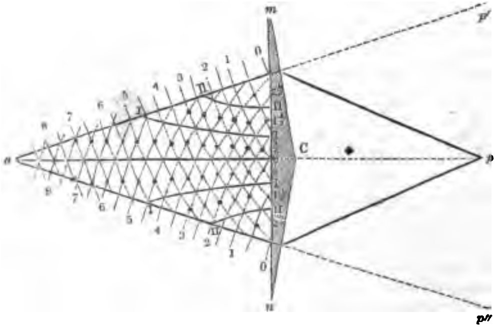
VII. INTERFERENCE OF LIGHT AND ITS EFFECTS.

§ 326.

By the *interference of light* is to be understood those effects which are produced by rays which proceed from the same source crossing one another at very acute angles after they have traversed either equal or unequal spaces. This interference of the rays has the remarkable effect of heightening the intensity of the light at many of the points of intersection, whilst at others it so lowers it that the light annihilates itself.

These effects are observable both in refracted and reflected light. The light of the luminous object appears then to be divided by dark stripes or circles, or other curves: if the light be simple, we see only bright stripes in the colour, separated by dark spaces between; but if it be either sun light, or any other white light, then the bright lines will be tinged with the prismatic colours.

Fig. 81.



The phenomena of interference may be displayed in refracted light by means of the following experiment of

Fresnel's: — If from a luminous point *p*, *fig.* 81., light be made to fall upon a prism *m n* c, having a very obtuse angle at c, and consequently very acute angles at *m* and *n*, then an eye at *a* would see the radiant point *p* double, viz. at *p′* and *p″*, in consequence of the ordinary refraction; but between these two images the spectator would observe a number of bright and dark lines perpendicular to a line joining the two images. If the source of light *p* be homogeneous, these bright lines have but one colour; but if it be white light that emanates from it, they will be tinged with the spectral hues. Cover half the prism with some opaque body, the intersection of the rays will cease, the lines will disappear, and only one image of the light will be visible.

Young first (1800) explained this remarkable phenomenon, and endeavoured by suitable experiments to establish his opinions on a scientific basis. The subject has since been prosecuted by Arago, Fresnel, Fraunhofer, and Herschel.

The explanation afforded of these circumstances by the corpuscular theory is both difficult and unsatisfactory; the other hypothesis, on the contrary, strongly recommends itself by the very lucid manner in which it enables us to account for the phenomena in question. The most essential features of this explanation may be expressed in a few words. The assumption is this, that the dark and bright lines of which we have been speaking are caused by two waves of æther or light crossing each other's path, when results follow corresponding exactly to what were produced by the interference of waves of fluids and sound. The two images *p′* and *p″*, *fig.* 81., of the radiant point *p*, observed through the interference-prism *m* C *n*, by an eye at *a*, are to be regarded as the centres of two similar systems of undulations, and the continuous arcs as bounding whole waves, whilst the dotted curves mark the half-waves. Admitting this, it follows that those atoms of light are in similar states of undulation which are at the distance of a wave asunder (see § 277.); and consequently, where the arcs of the entire waves intersect, as also where the arcs of the half-waves intersect, the undulations of the two systems correspond. In this case they mutually heighten each other's effect, *i. e.* they increase the brightness. Again, whenever the curves passing through the whole waves of one system cut the curves passing through the half-waves of the other system, the atoms of light meet with opposite velocity of vibration; these points of intersection are marked in the *fig.* by large dots. At each of these points, then, they counteract each other producing *interference*, which is made evident to us by the comparative obscurity of those parts. If the distances be closely observed of these bright and dark spots from p' and p'', the centres of the respective systems, it will be seen that the first bright stripes I I are at the distance of an entire wave from the line passing through the middle of the *fig.*; the next bright stripes I I I I are at a wave's length from the former, or of two waves' lengths from the middle line; and so on for all the successive bright stripes the distances will be 1, 2, 3, ... n waves' length. On the contrary, the lines of interference (marked by the large dots) will be at the distance of ½ a wave, 1½ wave, 2½ etc. waves; or, expressing it in general terms, those rays of light which produce interference, or dark stripes, are at the distance of ½, 1½, 2½ . . . . $n + \frac{1}{2}$ waves. Lastly, as the length of the undulations differs according to the colour of the light (§ 325.), it follows that the distances must also differ; in red light, the light and dark stripes will be almost as far again from each other as in violet light; in white light, then, alternations will closely succeed each other, and the stripes will consequently be of the prismatic colours.

§ 327.

The interference of the rays of light is the exciting cause of Newton's coloured rings as they are sometimes called; also of the prismatic colours observable in thin fish-scales, in spirit-of-wine if it be made to cover some dark surface in extremely thin films. These colours may also be seen in a drop of oil as it spreads over a surface of water, in pieces of crystal, especially in Iceland spar, rock-crystal, &c.; they are visible too in soap-bubbles, in thin blown-glass, on the surface of mother-of-pearl, on the wings of many species of insects, &c. These prismatic colours were produced by reflection in the Iris button invented by Barton, the entire surface of these buttons being divided into a vast number of fine grooves.

First Expt. To produce Newton's coloured rings, obtain a flattish convex lens (a watch-glass will do), and a piece of common window or plate glass. Press the two steadily together, and luminous rings will be seen about their point of contact, of the same colour with the incident rays, if the light be homogeneous. These rings are separated from each other by dark bands, as the light diminishes from the middle of each of the rings. The smaller the waves of light, the less the rings they generate; in violet light they are at a minimum, and in red at a maximum. In reflected light the point of contact is black; in transmitted light it is bright;

the rings which in reflected light appear luminous, are dark in transmitted, and vice versâ. If white light, or sun-light, be used in this experiment, there will be as many systems of rings as there are colours, in consequence of the unequal lengths of the undulations of the primary colours; these falling partly over one another, produce the compound colours. On comparing the reflected with the transmitted colours, it will be found that the latter are invariably the complementary colours to the former.

Second Expt. The spectrum that may be observed in splinters of glass or of crystal, or between the leaves of many crystalline bodies, as *ex. gr.* is common in the gypsum of Montmartre, is strictly analogous to the coloured rings of Newton, only that in these instances the colours are not separated by circular dark spaces, but by very irregular dark lines. — Similar effects may be produced by breathing on two plates of glass, and then pressing them tightly together. These figures will vary considerably in form, and if white light be used in colour also, if on pressing the plates together, one of them be moved along the surface of the other.

Third Expt. The spectral colours of a thin film of soap-suds show best in vacuo. Dr. Böttger describes the following mode of performing the experiment: — Put into a common pint bottle of white glass about ¼ of a dram of soap, scraped fine; on which pour about a couple of ounces of distilled water. Heat the bottle carefully, under a constant pressure, over a spirit lamp, till the soap is dissolved in the small quantity of liquid, and its temperature is raised nearly to the boiling point. Then skilfully close the bottle with a cork, which, on account of the rarity of the air within, had better be covered with a coat of sealing wax. Keep it in motion until the temperature sinks to 75° or 80° Fahr., and a bladder of soap will be produced, completely filling the interior of the bottle. The upper segments of the bubble display the most splendid coloured rings, which are produced by the infinitely minute particles of soap extending themselves in thin layers. The bubble may be kept sometimes for several days in the vial, without bursting. Observe that the bottle should not be held quite horizontally, and that the film of soap has not spread itself in a slanting direction, but lengthwise, to obtain the result in perfection. It is but right to add, that a first attempt may not prove successful; but expertness in making the bubble will be acquired with a little practice.

VIII. PHENOMENA DEPENDING ON THE DIFFRACTION OF LIGHT.

§ 328.

The deviation of the rays of light from their rectilinear course, in passing the boundaries of opaque bodies, so as to cast some portion of light on the shadows of objects, is termed the *inflexion* or *diffraction* of light. If the light be homogeneous, then dark stripes will be observable among the diffracted homogeneous rays, such stripes being parallel to the sides of the body which casts the shadow. If the light be white, the lines will be tinged with the prismatic colours.

Grimaldi, of Bologna (1660), was the first who noticed the diffraction of light. In modern times, the subject has been investigated, and explained by Fresnel, Fraunhofer, Herschel, and Schwerd.

Some of the simple phenomena, which are owing to the diffraction of light, may be verified by the following experiments:—

First Expt. Suspend an opaque black ball in the sun's rays, and the presence of light in the shadow which it casts will be very perceptible.

Second Expt. Hold a bit of fine wire, or a needle, or any similar object, close to one eye, the other being closed; and look steadily at it against any light back-ground, as a window, or a candle, and you will see several needles.

Third Expt. If sun-light be admitted through a very narrow crack into an otherwise dark room, several cracks will be visible at some distance from the real one, separated by dark bands from each other.

Fourth Expt. Make a rectilinear incision, with a sharp penknife, in a piece of cardboard. Look through the slit at the flame of a candle, and on each side of the real light others will be seen parallel to it, and marked with the spectral colours. This experiment may be rendered still more striking, by looking through the slit in the cardboard, directly, at a narrow cleft in the shutter by which the sun's rays are admitted into a dark room.

Results similar as to colouring and extent, but of greater beauty, are obtained by making the light to pass through several apertures, ranged close to one another.

Fifth Expt. Look at the flame of a candle through the thinnest part of a feather, and you will see several flames in a row: the brightness of their colouring will depend on the intensity of the light.

Sixth Expt. Look at any luminous point through a piece of fine cloth, and the light will be obviously inflected in a direction parallel to the texture of the material.

These phenomena can be explained, according to the corpuscular theory, only by calling in the aid of other auxiliary hypotheses with regard to the nature of light; since it is assumed that this diffraction is owing partly to an attraction and partly to a repulsion exerted by bodies on light in its passage past them. This explanation is unsatisfactory, as it fails to account for the origin of the dark intervening spaces.

The undulatory theory, on the other hand, regards all these phenomena as consequent upon the interference of light; and that when the waves of light impinge on solid bodies, they are disposed to propagate new undulations, which start from these points of incidence, and by crossing each other's paths, produce interference. Compare with this §§ 220. 222. 227., and especially what has already been advanced in reference to this subject in § 226.

IX. POLARIZATION OF LIGHT.

§ 329.

Light thrown back from reflecting plane surfaces, as well as that which, in its transmission through transparent substances, has undergone either ordinary or double refraction, possesses the following remarkable properties: —

1.) It is not perfectly reflected from a second reflecting plane, in every position in which such plane may be placed.

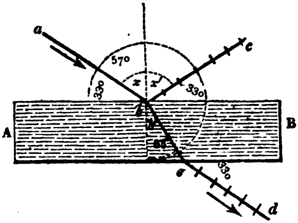
2.) It is not perfectly transmitted through a second transparent body, whatever the position of this second body; and lastly

3.) It is not doubly refracted by a body possessing this peculiarity (§ 313.), in every position that such body may occupy.

Light thus peculiarly reflected, or refracted, is said to be *polarized.*

This effect is produced in its highest degree, that is, light is *perfectly polarized* only when it falls on the reflecting or refracting plane, at some particular angle; which is called the *angle of complete* or *perfect polarization*. It differs, however, according to the nature of the body which causes the reflection, or refraction. According to Brewster, complete polarization obtains only when

Fig. 82.



the refracted ray, *b e*, *fig.* 82., makes, with the reflected ray *b c*, a right angle; so that angle *c b e*=90°, and angles $x+y=90°$.

According to Brewster's law just referred to, it follows that if *x*, *fig.* 82., be the angle of complete polarization, $y=90-x$, and consequently $\sin. y = \cos. x$. But from (§ 308.) $\frac{\sin. x}{\sin. y}$ expresses the index of refraction; substitute $\cos. x$ for $\sin. y$, and we have $\frac{\sin. x}{\cos. x} = \tan. x$; whence the law expressed verbally is, *the tangent of the angle of complete polarization is invariably equal to the index of refraction.*

From these data we can readily determine the angle of complete polarization for any substance, if we only know its index of refraction. Thus, *ex. gr.*, according to the table of indices in § 300., the index for atmospheric air is 100,028; that for glass, 153,200; and for water, 136,600: consequently, the angle of complete polarization for air and glass is $\tan. x = \frac{153200}{100028} = 56° \, 51'$; and for air and water, $\tan x = \frac{136600}{100028} = 48° \, 17'$.

§ 330.

That plane in which a polarized ray is capable of being completely reflected, or transmitted, at its proper angle of polarization, from a second plane which intercepts the ray, is termed its *plane of polarization.*

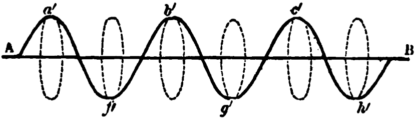
Every ray of polarized light has one plane of polarization for its reflection, and another for its refraction; and these two planes are at right angles to each other: a reflected and a refracted ray are therefore *polarized at right angles to each other.* If the planes of reflection and refraction are perpendicular to the plane of polarization of the incident ray, in that case the polarized ray will be neither reflected from the transparent body, nor transmitted through it: the *ray is then said to be polarized in a plane perpendicular to the planes of reflection and refraction.*

The two rays of a ray divided by double refraction are both polarized; but at right angles to each other. The ray of ordinary refraction lies in the plane of the principal section, whilst the ray of extraordinary refraction is polarized in a plane vertical to the former. (§ 314.).

To explain the causes of the polarization of light is among the greatest difficulties in the whole science of optics. The most simple and satisfactory explanation is that afforded by the undulatory hypothesis. The principal phenomena will be accounted for as we come to them, in accordance with this theory. We may at once explain how the æther is supposed to vibrate in polarized light.

It is assumed, that in non-polarized or common light the particles of æther vibrate every way in the direction in which the waves are propagated (§ 277.), but that in polarized light the motions take place only in two opposite directions. The plane in which these excursions take place is called the *plane of vibration;* if a plane be conceived to be situated at right angles to the plane of vibration, and in the direction of the ray, this will be its *plane of polarization.* Hence it follows that the vibrations of the particles of polarized light take place perpendicularly to the plane of polarization. Let A B, *fig.* 83., be a ray of polarized light, and the surface of the paper its plane of vibration, then the curve $a' f' b' g' c' h'$ will represent the atoms of æther vibrating in this plane at some particular moment, and a plane placed at right angles to the paper in the line A B would be the plane of polarization for that particular ray.

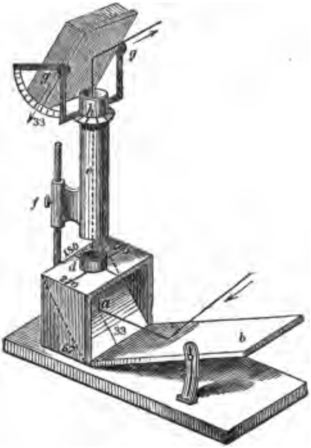
Fig. 83.



Instruments contrived for the exact and convenient observation of these phenomena and others shortly to be detailed, as also for the measurement of the angle of polarization, are called *polariscopes.* They are variously constructed, but Baumgartner's is, perhaps, among the best for its simplicity, as well as for its convenience and accuracy in the management of observations.

Its construction in the main is, first, a plane mirror *a, fig.* 84., of glass, blackened on the back and varnished, which is inclined at an angle of 57° to the horizon; this mirror receives the light reflected on it by a common looking-glass *b*, at an angle of 33°; these rays it polarizes and projects vertically upwards. The polarized ray passes through the circular aperture *d* up the tube *e*, which is blackened inside, and which may be raised or lowered at pleasure up and down the pillar *f*. Over the upper end a ring *h* passes, which is moveable about an axis, and carries a frame *g*, containing either a blackened glass mirror like the former, or else some 10 or 12 glass plates, laid smoothly one upon the other. This frame may be placed at different angles with the axis of the tube. This part of the apparatus must be so contrived, that for it we may be able to substitute a crystal of double refraction (an achromatic prism of Iceland spar is the best), which is set in a ring, and may be turned about in the upper opening of the tube. Substances through which we wish to conduct the polarized ray are laid on a glass set in a ring at *d*, so that they can be turned about the axis of the polarized ray. An account of Biot's apparatus will be found in his *Traité de Physique*.

Fig. 84.



A. *Reflection and Refraction of Polarized Light.*

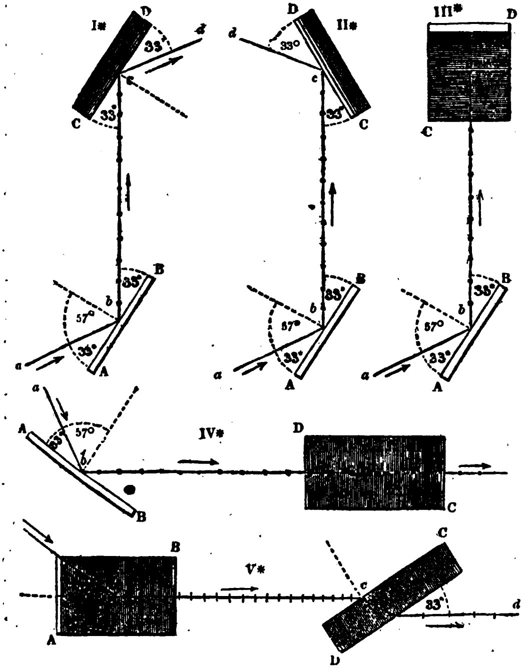
§ 331.

If polarized light be reflected, we shall find

1.) That a ray of light falling under the angle of complete polarization on the first polarizing mirror, and being reflected thence, will be completely reflected also from the second mirror, if the plane of its incidence against the first mirror coincide with the plane of its reflection from the second.

2.) The second mirror does not reflect the light polarized by the first, when the planes of incidence and reflection are perpendicular to each other.

Fig. 85.



Let A B, *fig.* 85., be the mirror of polarization, *a b* an ordinary ray incident upon it, and *b c* the polarized ray reflected from it. This ray will be reflected from the second or reflected mirror C D, in the direction *cd*, if C D be parallel to A B as I*, and again when it has been turned 180°, or a half circle from that position as II*. In both cases, according to 1.), the incident, the polarized and reflected rays *a b*, *b c*, and *c d* are in one and the same plane; in fact, according to the diagram in the plane of the paper's superficies.

But if by 2.) the reflecting mirror make an angle of 90° with the mirror of polarization, or if these two cross each other as C D, III* represents, then C D will not throw back the polarized ray *c d*, which falls upon it at *c*, because its plane of reflection, as the drawing shows, stands perpendicular to the surface of the paper. The like result follows from similar causes, if the mirror be turned round 270°.

Hence it follows, that during one entire revolution of the second or reflecting mirror about the polarized ray which falls upon it, it comes into two positions, such that the light thrown on it from the first mirror will be completely reflected, and in two other positions in which the incident ray will be absorbed. If we mark the first position, in which the mirrors are parallel to each other, and in which complete reflection obtains, with zero, then at 90° from that point the reflection will be *nil*, at 180° it will again be complete, and at 270° again *nil*. In any intermediate position the reflection will be partial, and the nearer the ray to the angle of refraction 90° or 270°, the more feebly is it reflected. According to Malus, the intensity of the reflected light is invariably proportional to the cosine* of the angle formed by the inclination of the first plane of incidence with the second.

If several plates of white glass, laid one on the other, be substituted for the reflecting mirror, the light polarized by reflection will present the following appearances: —

1.) The light reflected from the first mirror is not transmitted through the glass plates if its plane of refraction coincides with, or is parallel to the plane of reflection of the first or polarizing mirror, as C D in *figs.* I* and II*.

2.) The maximum of the light polarized by the first mirror is transmitted through the plates of glass, when the plane of its refraction is perpendicular to the plane of reflection of the first mirror, *i. e.* when the glass plates have the position C D in IV* and V*.

Hence it appears, that a ray polarized by reflection is transmitted through glass when its position is such that it cannot reflect the light; and, conversely, that it is not transmitted through the glass plates if it can be reflected from their surface.

§ 332.

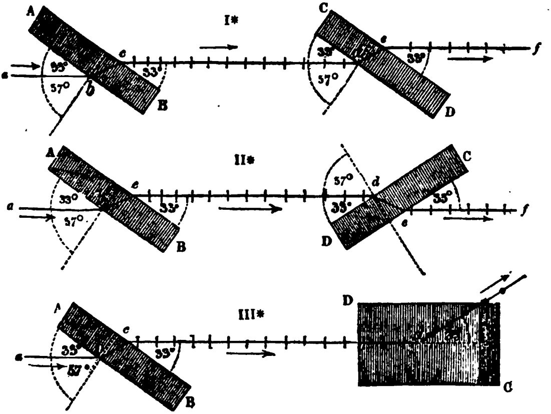
The following are the phenomena to be observed with regard to rays of light polarized by refraction:

1.) Light which has become polarized by passing at the proper angle through several plates of white glass, ranged one upon the other, will be transmitted through a similar system of plates, if the plane of refraction of the first system coincides with that of the second.

2.) Light polarized by the first system does not pass through the second, if the planes of refraction of the two systems of plates stand at right angles to each other.

Let A B, *fig.* 86., be the first system of glass plates, on

Fig. 86.



which an ordinary ray *ab* falls at the angle of complete polarization, *bcd* will be the ray polarized by refraction.

In the first case the ray passes through a second system of glass plates C D, if it be parallel, as I*, to A B, or if, as II*, it be turned round 180°, or half a circle. In both cases the planes of refraction of A B and C D coincide, *i. e.* *b c* and *d e*, with the polarized ray *c d*, lie in the same plane, and in the diagram in the plane of the paper.

But if the second system of glass plates C D be at an angle of 90° to the former, as in III*, then the ray incident at *d* is not transmitted, for its plane of refraction as the figure shows, is perpendicular to the plane of the paper.

Hence we infer, that light polarized by refraction obeys the same laws with regard to a second refraction, as light polarized by reflection did with respect to a second reflection.

In the place of the second system of glass plates put a reflecting mirror: or, if you please, observe the ray reflected from the first glass plate, and you will find that:

1.) The light transmitted through the first system will not be reflected by the second, if the plane of reflection coincide with the plane of refraction, as in positions I* and II*, where the plane of refraction of A B, and that of reflection of C D, are supposed to lie in the surface of the paper, and

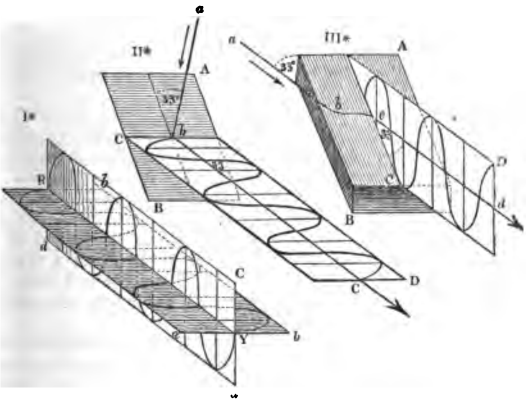
2.) That, on the contrary, the mirror, or the outermost plate of the second system, reflects the ray polarized by the first, if the plane of reflection be at right angles to that of refraction, as C D in III*, the plane of reflection in this case being vertical to the paper.

A similar relation appears to obtain with regard to light polarized by refraction, as we found to exist in that polarized by reflection; since the ray which the first system of plates had polarized will not be reflected from the second, if its position be such as to admit of the transmission of the light; and conversely, that when transmission is impracticable, the ray is reflected; and lastly, that this reflection occurs just at that point in the system of plates at which light, polarized by reflection, would have been transmitted.

From the phenomena respecting the polarization of light by reflection and by refraction, explained in the preceding sections, it is clear that this condition may be induced by two distinct modes; and further, as has been already remarked in § 330., the plane of polarization, and the planes in which the reflected and refracted rays vibrate, are invariably at right angles to each other. Thus, the particles of æther in a ray polarized by reflection vibrate in a plane which stands perpendicularly to the plane of reflection of the first or polarizing mirror; whence the plane of such a ray's polarization and its plane of reflection coincide. The particles of a ray polarized by refraction vibrate in the plane of refraction; and their plane of polarization is vertical to it.

Let R Y, *fig.* 87. I*, be a ray: it will be polarized in the two planes *a a b b* and *c c d d*, which cut each other vertically. Suppose *a a b b* to be the plane of vibration for the ray polarized by reflection; then the serpentine line drawn upon it will be the curve of vibration and intensity of the polarized particles, *c c d d* being their plane of polarization. In like manner, *c c d d* will be the plane of vibration, and *a a b b* that of polarization, for the ray polarized by refraction. If A B, *fig.* 87. II*, be a perspective representation of a polarizing mirror, on which a ray, *a b*, falls at the proper angle; *b c* would be the reflected polarized ray, and C D would be its plane of vibration; the curve which is drawn on it expressing the vibrations of the polarized particles of æther. *Fig.* 87. III* is a similar representation of a refracted polarized ray: A B is the system of glass plates; *a b* the ray incident thereon at the angle of complete polarization; which, being refracted in the direction *b c*, is propagated towards *c d*, as a ray polarized by refraction. The plane C D, at right angles to the glass plates, will be its plane of vibration; and the curved line depicted on it will be the curve in which the polarized particles move.

Fig. 87.



Now, as a ray which falls on several plates of glass is partly reflected and partly refracted, it is clear that it must undergo a double polarization. *Fig.* 82. will render this more evident; if we suppose A B to be the system of plates viewed transversely, and that the system itself stands vertically to the surface of the paper; which would, in this case, represent the plane of reflection and refraction. A ray, *a b*, falling on these glass plates at the proper angle, will be polarized in a plane perpendicular to the paper, and reflected in the direction *b c*; it will also be refracted towards *b e d*, being polarized in the plane of the paper. We must also conceive the plane of vibration of the reflected ray *b c* to be perpendicular to the surface of the paper; the points marked on the line indicating the directions in which the particles of æther make their excursions. The plane of vibration of the refracted ray *b e d* will be the paper itself; and the cross lines on *b e d* show the deviations of the vibrating particles of æther.

When polarized light impinges on a second reflecting surface, or on a system of glass plates, it will not be reflected or refracted, as the case may be, unless it can propagate its undulations in a similarly situated plane of vibration. If this plane be at right angles to the former, the light becomes absorbed; but this depends on the angle that the ray, already polarized, makes with the plane on which it falls, and on the completeness of the second polarization. Such a ray will therefore be entirely unreflected by the second plane, or untransmitted through it only at the angle of complete polarization.

The phenomena described in §§ 331 and 332. will now have been rendered altogether intelligible; and if the signification be borne in mind, of the dotted and crossed rays, given above, *figs.* 85 and 86. will become more easy of comprehension.

§ 333.

If polarized light be admitted through a small aperture, on a rhomboedron of calcareous spar, or, better still, on an achromatic prism; an eye behind the prism or crystal will, in two positions that it may be made to assume, see but one image of the aperture; in all other positions two images will be visible. In the position in which only one image of the aperture is seen, but one of the rays produced by the double refraction (§ 314.) is transmitted; the other ray not passing through the crystal.

If the principal section of the crystal lie in the plane of reflection of the polarized light, but one image of the aperture will be visible, viz. that which is produced by the ordinary refraction;

in other words, in this position the ordinary ray alone is transmitted. Turn the crystal round, and you will see two images of unequal brightness. If the principal section of the crystal make, with the plane of reflection, an angle of 45°, both the openings will be equally bright. On turning it further, the ordinary ray becomes more faint, and when the crystal has revolved 90° from its original position, so that its principal section is at right angles to the plane of reflection, the ray of ordinary refraction vanishes; one aperture only is visible, because, when placed thus, it is only the extraordinary ray that is transmitted. With every quarter turn one image disappears, and the other attains its maximum intensity. If light, polarized by refraction, pass through a crystal of this kind, the same phenomena present themselves; with only this difference, that the ray of extraordinary refraction is transmitted in that position of the crystal in which the ray of ordinary refraction was transmitted when the light was reflected; and vice versâ.

Double refraction, therefore, polarizes both the rays, into which a ray of natural light is divided, in planes vertical to each other; in the case of reflected light causing the ordinary ray to be propagated in the direction of the principal section, and the extraordinary ray in a plane perpendicular to the former.

In *fig.* 66. (by § 314.) $m\,l$ is the ray of ordinary, and $m\,f$ that of extraordinary refraction. The points and cross lines marked on these rays, according to the explanation in the preceding section, represent the vibrations of the polarized particles of æther; and if we conceive of the spar being substituted for the second or reflecting mirror of the apparatus, we shall at once see how the phenomena described in that section originated.

There are other bodies resembling the Iceland spar, which possess the property of double refraction; the most important of them is *tourmaline*. This substance crystallises in long prisms, the axis of whose figure is also the axis of refraction. For this purpose the crystal is split into thin plates parallel to the axis. Every polarized ray falling vertically on such a plane is transmitted with undiminished intensity, if its plane of polarization be perpendicular to the axis of the tourmaline; but if this plane be parallel to the axis of the crystal, the ray ceases to be visible. In all intermediate positions, its intensity is increased or diminished, as the angle made by the plane of polarization is greater or less. A leaf, such as we have described, will be found a very convenient piece of apparatus for testing the double refracting power of other crystals which may be divided into thin plates.

B. *Chromatic Phenomena attendant on the Polarization of Light.*

§ 334.

If polarized light be transmitted through very thin plates of perfectly crystallized bodies, which have been split or cut in the direction of their primary axis of crystallization, as *ex. gr.*, through leaves of gypsum, or mica; this light, on being polarized a second time, displays new properties; for, on turning round the crystal, or the second mirror of polarization, or the system of glass plates, as the case may be, there will arise an alternation, not merely in the intensity and dimness of the light, but also in its colours.

In all those positions in which the primary section of the crystal forms an angle of 0°, 90°, 180°, and 270°, with the plane of reflection of the first mirror, *i. e.* when the plate of crystal either coincides with the plane of reflection, or is vertical to it, the image or ray appears bright in the second mirror, if it be so situated that its plane of reflection coincides with that of the first mirror. If, on the contrary, the mirrors be so situated that their planes of reflection stand at right angles to each other, then it appears dark in the second mirror, in the same position of its principal section. These phenomena will be reversed, if the light which passes through the plate of crystal fall upon a system of glass plates at the proper angle of polarization; that is to say, it will be dark through the glass plates, if they be placed in such a manner as rendered the second mirror bright; and if they be in that position in which the second mirror was dark, they become bright.

Turn the plate of crystal in its own plane, right or left, around the polarized beam, so that it may occupy a position distinct from those already mentioned, and the most beautiful simple colours will be seen, those of the reflected ray being invariably complementary (§ 318.) to those of the simultaneously transmitted ray. The colours attain their maximum intensity at every half-quarter turn, *i. e.* when the principal section of the crystal deviates 45° from the positions named in the preceding paragraph. If the second polarizing mirror, or system of glass plates, be turned one quadrant from that position in which it showed the colours most brightly, the colours of the reflected and transmitted rays will be exchanged.

From what has been said, it is evident that in one entire revolution of the plate in its plane, and also in one entire revolution of the second mirror, or system of glass plates, the light undergoes eight changes, being most intensely coloured at the octants, but at the quadrants appearing colourless or dim.

Substitute an achromatic prism of Iceland spar for the second mirror, and you will see two images of the plate. If the sections of the plate of crystal and of the Iceland spar lie in the same plane one above the other, or if they intersect at right angles, one image is bright and the other dim. If either the thin plate or the spar be made to revolve about the polarized ray, the two images are tinged of the complementary colours; at every quarter turn under 45° the colours acquire their greatest degree of brightness, and when they partially lie over each other they are white.

These phenomena, as well as others to be mentioned in the following sections, may be most conveniently observed if the fine plate of gypsum, mica, or other transparent crystal be placed on the glass which covers the aperture *d* of the polarization instrument, described in § 330., and turned round with it.

The kind of colour shown by these bodies depends on the thickness of their leaves; at a certain thickness, Biot says about $\frac{1}{30}$th of an inch, they are colourless, the vivacity of the colours increases as the density diminishes, until they are rendered too thin, when the colours again vanish. They appear of a single colour only when the thickness is uniform; if this be unequal the colours also vary. This peculiarity is most evidently displayed in a wedge-shaped polished piece of gypsum, one end of which should be so thick as not to produce any colour, whilst the other end, for an opposite reason, is also destitute of colour; all the colours answering to the different thicknesses of the crystal will be seen in a regular succession of bright and dark stripes, the intensity of the colours increasing in proportion to their nearness to the thin end of the plate.

These phenomena of colours, and especially the last noticed, as also those which will come under our consideration in the succeeding sections, possess a striking analogy with the prismatic rings of Sir I. Newton, described in § 327. The undulatory theory attributes these appearances to the interference of the waves of polarized light, which are retarded in their passage through the fine plate of crystal.

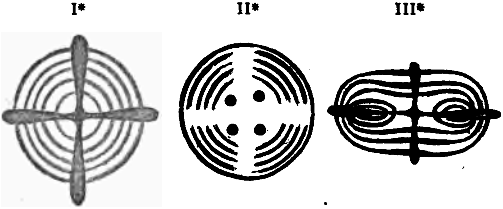
§ 335.

Spectra more beautiful than those we have yet described, characterized too by their possessing definite figures, may be obtained by transmitting the polarized light through a slice of the crystal cut at right angles to its axis, the light being made to pass in the direction of the axis. On the second polarization of the light transmitted through these plates they will exhibit several concentric rings of varied colours, closely resembling

Newton's prismatic rings, and intercepted in the middle by a rectangular cross. This cross is either white or black, and the rings are always composed of the complementary colours. The cross seen in the second mirror, or through the system of glass plates, will be white, if the mirror or plates be so placed as to reflect or transmit the ray polarized by the first mirror; it will be black if the light be absorbed or unable to continue its course. Both the images will be seen simultaneously through an achromatic prism of Iceland spar, which will best display the complementary colours of the rings.

Coloured rings are formed about both the axes of such crystals as have two axes, their centres being intersected sometimes by but one straight or curved line, instead of by two in the form of a cross.—I * and II *, *fig.* 88., represent the arrangement of the rings in crystals having but a single axis; III * that which obtains in crystals having two axes.

Fig. 88.



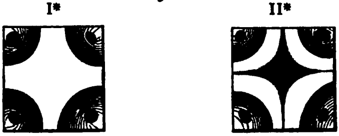
§ 336.

If a polarized beam be transmitted through a transparent uncrystallized body, as *ex. gr.* through glass, no such change as we have just described occurs in the light. From this fact, as well as from the explanations given in the previous sections, it seems that these phenomena are intimately connected with the internal crystalline structure of the transparent medium. If a modification be induced in the internal arrangement of these substances, by the application of heat or pressure, or otherwise, they exhibit chromatic phenomena closely resembling those of crystalline bodies. Professor Seebeck, who discovered this property, has given to the figures thus formed the name of *entoptic coloured figures.*

This peculiarity may be rendered permanent in glass by heating it until it becomes soft, and then cooling it quickly in the air.

I* and II*, in *fig.* 89., represent the figures obtained by rapidly cooling a square piece of glass. I*, *fig.* 89., further represents the image depicted on the second mirror of polarization when in the position shown in *fig.* 85. I* and II*, as *fig.* 89. II* does that represented in the position III* of the same *fig.* 85. Thus it is easy to determine what figures belong to light transmitted through the system of glass plates when placed in any of these principal positions.

Fig. 89.



The discovery of the phenomena attendant on the polarization of light as produced by its reflection from glass is due to Malus, 1810; Arago, in 1811, first noticed the peculiarities in the colours of polarized light, since which time these remarkable properties have been investigated by Brewster, Biot, Fresnel, Herschel, Seebeck, and others. The limits within which it is proper that this volume should be kept are too narrow to allow of our entering more fully into the details of these extraordinary phenomena, which have contributed in so high a degree to establish on a firm basis the credibility of the undulatory theory as to the nature of light; we must, therefore, pass over *elliptical* and *circular polarization*, referring the reader for further information on these subjects to the works of Biot, Pouillet, Brewster, Herschel, and others.

X. OF THE STRUCTURE AND FUNCTIONS OF THE HUMAN EYE.

§ 337.

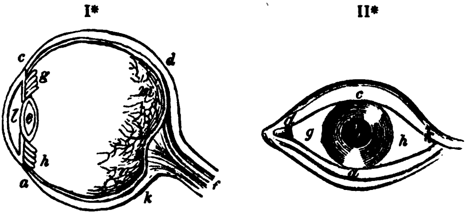
By the sense of sight, *i.e.* through the medium of nerves formed for that purpose, we are rendered sensible of the *presence* of external objects, and also of their *form, colour, movement, size, distance,* and *position.*

The organ by which all this information is conveyed to us is the *eye*, which is a beautiful piece of natural dioptric mechanism; in other words, its efficiency depends on its capability for refracting light. From a knowledge of its construction we learn how it acts as an optical instrument, and hence also we explain in some degree the theory of vision.

The *eye-ball* is nearly spherical in figure, and consists of several coats or membranes; but a small part of the outer portion of this coat is transparent so as to admit the light into the interior of the eye. This space is filled up with two colourless fluids or humours, separated from each other by an intervening membrane. In the middle of this partition is a small circular aperture, behind which is a transparent substance having the shape of a double convex lens. Opposite to this lens and the pupil, or hole for the admission of light, is the optic nerve, which enters through the back part of the outer coat, and extends itself over the inner surface of the eye. The eye lies in a cavity surrounded by solid bones, and is set in motion by several muscles; the nerves of both eyes unite in a common cord.

Fig. 90. I* is a sectional and II* a front view of the eye. The same letters are used in both the diagrams to mark the different parts.

Fig. 90.



The outermost thick membrane *a k d c* is called the *sclerotic* coat; it constitutes the white of the eye; the projecting transparent part *a b c* is the *cornea*. The lens-shaped body *e* is the *crystalline lens* or *humour*, a cartilaginous transparent mass, suspended in a delicate transparent capsule. The interior of the eye is divided into two unequal chambers by the *ciliary processes g h*. The *anterior* and lesser chamber *a l c* is occupied by the *aqueous humour*, and the larger or *posterior* chamber *g m n h* with the *vitreous humour*. The former fluid is as limpid as water, the latter somewhat gelatinous; both are however colourless, highly transparent, and differ but little from water in their refractive powers; this also is the case with the crystalline lens. The interior surface of the sclerotic is lined with the *choroid* coat *g m n h*, which is covered with a black slimy pigment, by which the reflection of the light that enters the eye is prevented. This choroid coat extends as far as the cornea, *i. e.* to the ciliary processes, which suspend the sac containing the crystalline humour. Between this lens and the cornea is the *iris k l a*, in the middle of which is the *pupil l*, a round opening, having the power of dilating and contracting itself, according as the intensity of the light varies. Viewed on the exterior the iris of the human eye appears as a ring of different colours. The *optic nerve f*, which goes through the sclerotica, spreads itself out on the inner surface of this coat in a reticulated form, and is called the *retina m n*. The nerves of the two eyes join in a common cord, and so communicate with the brain.—The eyes of warm-blooded animals resemble in their construction the same organs in man. By dissecting one of their eyes, as that of an ox, the various parts may readily be distinguished.

§ 338.

Since we now know the construction of the eye, we can infer from the laws of refraction the mode in which images of objects are formed in it. If a pencil of rays from any luminous point fall upon the eye, those rays which pass through the pupil become refracted by the crystalline humour in the same manner as by any other double convex lens, that is to say, they converge and meet at a point on the other side of it; they also suffer a refraction in the other two humours, between which the crystalline lens is situated. According to the laws of refraction (§ 311.) there will be formed in the interior of the eye a *small inverted image* of every self-luminous or illuminated object.

That such an image is actually formed in the interior of the eye follows from what has been already said. How the sensation of these images and their colours is communicated to us we cannot exactly say, as we are but imperfectly acquainted with the nature of light itself. Probably, however, the sensation of images and colours is owing to an irritation which the light produces in the fine threads of nerves which are spread like a delicate network throughout the interior of the eye, and thus the irritation is communicated to the brain. Some philosophers are of opinion, that this irritation is owing to the thermal and chemical influence of light. According to the undulatory theory, the cause is supposed to be, that the particles of æther in the eye being put into a state of undulation, not only communicate this motion to the optic nerve, but that, by the different velocities with which they undulate, they excite the sensation of colours in a manner similar to that in which a variety of notes is produced.

§ 339.

The perception of objects is *not* owing to our *seeing* their images depicted on the retina, for to do this we should require a second eye placed behind the first; the consideration of this fact, that we do *not* actually *see* the images in our eye, will render it less difficult to understand why the object viewed appears erect, although its image is inverted. If an object be seen in a plane mirror, we know that our judgment assigns to its parts a position according to the direction in which the rays of light they project strike the eye: in like manner, when rays descend to our eye, and thereby depict an image on the lower part of the retina, we are conscious that it is from the upper part of the object they were projected; and, conversely, those rays which enter from below, and form an image on the upper part of the eye, we invert and refer for their origin to the lower part of the object.

NOTE. Müller decidedly objects to the explanation given in the text, saying in his *Elements of Physiology* (translated by Dr. Baly), part v. p. 1171., "The hypothesis, that erect vision is the result of our perceiving, not the image on the retina, but the direction of the rays of light which produce it, involves an impossibility, since each point of the image is not formed by rays having one determinate direction, but by an entire cone of rays; and, moreover, vision can consist only in the perception of the state of the retina itself, and not of any thing lying in front of it in the external world"

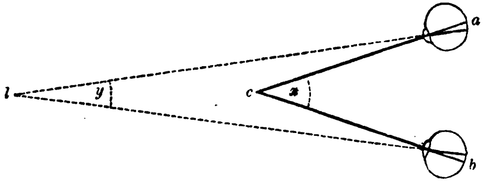
The professor thus explains his own view of this subject by saying, "—— even if we do see objects reversed, the only proof we can possibly have of it is that afforded by the study of the laws of optics; and that, if every thing is seen reversed, the relative position of the objects of course remains unchanged. It is the same thing as the daily inversion of objects consequent on the revolution of the entire earth, which we know only by observing the position of the stars; and yet it is certain that, within twenty-four hours, that which was below in relation to the stars, comes to be above. Hence it is, also, that no discordance arises between the sensations of inverted vision and those of touch, which perceives every thing in its erect position. Even the image of our hand, while used in touch, is seen inverted. The position in which we see objects, we call therefore the erect position."

Volkman even argues that no explanation of erect vision is required, for "nothing can be inverted where nothing is erect; each idea exists only in antithesis to the other."

§ 340.

A second question arises, which is this: How is it that we do not see a double image of the object viewed when we use both eyes? This case resembles that of erect vision. When we look at any object, each eye arranges itself so that the axis of its crystalline lens intersects the object. Let *a* and *b*, *fig.* 91., be the two eyes, and *c* any object before them; then *a c* and *b c* are their axes, which meet in *c*. An image is consequently produced in each eye, behind its crystalline lens, which will correspond with the perspective projection of the object from the points *a* and *b*. Thus, as both these images are conveyed to our sensorium through the medium of the optic nerve, we throw them back inverted to *c*, the point of intersection of the optic axes, where, as they coincide, they excite simultaneously the sensation of the object in our mind.

Fig. 91.



Mr. Wheatstone made use of an ingenious and extremely simple instrument, called the *Stereoscope*, which may serve to prove the accuracy of these deductions. It consists of two plane mirrors, inclined with their backs to each other, at an angle of 90°; perspective drawings of an object are placed at the sides of the mirrors, and at equal distances from them in the same horizontal line; the spectator placing his head against the edges of the two mirrors, will see a single image of the solid represented by the drawings.

An object will be seen double if the eyes are set so that their axes may meet either before or beyond the object; or the same effect is produced by withdrawing one of them from the line joining the eye and the object. The following experiments will verify this.

First Expt. Place a lighted candle at a distance of from 6 to 8 paces off, and look at it with both eyes, it will appear single. Now place one finger before the eyes from 8 to 10 inches from them, and look steadily at it, you will see a candle on each side of your finger. Referring to *fig.* 91., *c* may represent the finger, and *l* the light; then the optic axes must be directed to *c* to see the candle plainly. The rays from *l* producing images at *m* and *n*, lying beyond the axes, cause two lights to be seen, one on each side of the finger.

Conversely, the finger may be viewed double, by directing the optic axes to the light.

Second Expt. Look at any object with both eyes, and then press the ball of one eye, by means of your finger, slightly out of its place, and in the eye under pressure a second image will be produced, or the image already existing there will assume a new position.

§ 341.

The conditions which must be fulfilled, in order to the image of any object being perceived by the optic nerve, and thus transmitted to our sensorium, are the following: it must be sufficiently *distinct* and *luminous; it must fall directly on the retina; it must have an adequate magnitude,* and *remain a sufficient length of time on the retina.*

§ 342.

Images to possess the requisite degree of *distinctness* must, especially, be free from spherical aberration. (§ 309.) To this the form of the crystalline humour, the position of the iris, which serves as a blind, and, lastly, the concave figure of the retina, all contribute. The prismatic dispersion of the light is not absolutely annihilated, but as the images are formed on the retina in the axis of the crystalline lens, or very near to it, the refraction of the rays causes an almost infinitely small dispersion.

§ 343.

An image is sufficiently *illuminated* when the object that produces it sends, or is capable of sending, the requisite quantity of light into the eye. If the light be too intense the pupil con-

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NOTE. Any one may satisfy himself that the eye is not perfectly achromatic, by looking steadily at a piece of paper on which large characters have been written or printed, the eye being adjusted for a distance different from that at which the paper is held; the letters will appear to have prismatic fringes, and the less distinct the images the more deeply are the fringes coloured.

tracts, and admits but a small portion into the eye; if, on the contrary, it be but weak, the pupil dilates so as to receive more rays. There are limits, though far asunder, for if the light be either insufficient or too powerful, in either case the eye is incapable of distinguishing objects.

The extremes at which the organ, in a healthy condition, is capable of reading print, are in the light of the full moon, and in that of the sun at noon, these intensities being to each other as 1 : 300,000.

Hence we can understand how it is that we are able to see objects in a room which has been suddenly darkened, or into which one comes out of the sunshine. The sudden over-excitement of the optic nerve by intense light sometimes produces blindness, and is always hurtful to the sight. Many species of animals, *ex. gr.*, fishes in the depths of the sea, and beasts of prey who prowl by night, are able to see objects with a much less degree of light than we can.

§ 344.

We know that the images produced by a convex lens appear distinctly only at a certain distance from the lens. (§ 311.) When the object is near the distance is increased, and inversely. Since the crystalline humour is precisely such a lens, it is evident that if its form and position remain unaltered, a distinct image can be produced on the retina only when an object is at one precise distance from the eye; but experience tells us that objects are clearly seen at distances extremely unequal; hence we infer that some provision exists by which the eye accommodates itself to the distance at which an object may be situated. Whether this is effected by some alteration in the form or position of the crystalline lens, or whether the retina is thus modified, is uncertain; but that some adaptation of this nature does exist, would appear from considering that, when we look suddenly at a remote object, after having observed one near to us, and vice versâ, in neither case do we instantaneously see the second object distinctly. These changes depend partly on our volition, and partly on the sensation produced by the light. This self-adjusting power of the eye is exerted only within certain limits.

§ 345.

The distance at which objects can be seen distinctly, or the "distantia visionis distinctæ," is with most persons from 8 to 10 inches. Objects nearer than this are either not seen distinctly, or are so seen by a painful effort.

"Myopia," or near-sightedness, is that condition of the eye, peculiar to some persons, in consequence of which they see objects distinctly at less than the usual distance of distinct vision; the opposite imperfection is "presbyopia," or far-sight. The subjects of the former infirmity receive no distinct impression of objects beyond the range at which they see distinctly, for the images of such objects fall *in front* of the retina. Far-sighted persons, on the contrary, have no distinct image of objects at a distance of from 8 to 10 inches from the eye, because their image is projected *beyond* the retina. To remedy these natural defects, the latter class should make use of *convex lenses*, by which the rays of light would be brought sooner to a focus, so as to meet on the retina; and the former class should employ *concave* spectacles, by which the rays would be rendered more divergent, and would, consequently, meet on the retina instead of before it.

The principal cause of either long or short sight will be found to be the nature of the employments in which the eyes are principally engaged. If spectacles are used to aid imperfect vision, those ought to be selected which exactly remedy the defect to which the individual is subject. The choice must therefore depend on the distance of distinct vision of the unaided eye, and also that at which it is wished to see objects plainly with the aid of the spectacles. Let α represent the natural distance of vision, and a that which it is wished to attain; then the radius r of the spectacles which would suit the eye would be, if double convex, $\frac{1}{r}=\frac{1}{a}-\frac{1}{\alpha}$ (see § 312. under A 4); or if double concave, $-\frac{1}{r}=-\frac{1}{a}+\frac{1}{\alpha}$ (§ 312. B).

If the distance of distinct vision of a far-sighted person be 12 in., and he wishes by the aid of glasses to see objects distinctly at 8 in., then $\frac{1}{r}=\frac{1}{8}-\frac{1}{12}$, or $r=24$ in.; *i. e.* he must use a double convex lens, having a focal distance of 24 in. — Conversely, if the distance of distinct vision of a near-sighted person be 4 in., and he desires to see objects distinctly at 8 in., $-\frac{1}{r}=-\frac{1}{4}+\frac{1}{8}$, or $r=8$ in., *i. e.* he would require a double concave lens, whose focal distance is 8 inches. Spectacles can, of course, be made to render objects distinctly visible at greater distances, but they are decidedly injurious to the sight. In case such should be required, their radius may be found for any particular distance in the manner shown above.

The inverted image on the retina may be seen by paring off, with a sharp knife or razor, so much of the sclerotica of an ox's eye as renders the remaining portion transparent. Now hold the cornea at a proper distance opposite to any luminous object, as the flame of a candle, and you will have a small inverted image of the flame distinctly visible on the transparent part of the sclerotica.

An artificial glass eye, which may be procured at the opticians, will be found convenient in illustrating the functions performed by the different parts of this organ, as also for showing how convex and concave glasses remedy the opposite defects of long and short sight.

Sometimes the retina becomes partially or entirely insensible to the impressions of light. This morbid condition of the organ is termed *amaurosis*. *Cataract* is another disease to which the eye is liable. It consists in a thickening of the crystalline humour; in consequence of which light is either imperfectly or not at all transmitted to the retina. This disease is cured by couching, *i. e.* either by extracting or depressing the lens, and using very convex glasses to discharge the proper office of the crystalline humour in a healthy state.

§ 346.

To the production of a distinct image on the retina, it is further requisite that it be of a certain magnitude, which will depend on the susceptibility of the eye, and on the illuminating power and colour of the object. The image of an object moderately illuminated must be 0·001 of an inch long, or the extreme rays of light must form an angle of ½ a minute in the eye at a minimum; whence it follows that an object of mean illuminating power will be visible if its distance from us is not more than 68 or 69 thousand times its greatest length. Strongly luminous bodies, such as the fixed stars, are visible at infinitely small visual angles; they excite in the eye merely a sensation of light, without creating any impression as to their apparent magnitude.

Plateau asserts that white may be distinctly seen in the light of the sun at an angle of $12''$, yellow at one of $13''$, red at $23''$, and blue at $26''$; but that in ordinary day-light these angles must be ½ as large again.

§ 347.

Light must act upon the eye for a certain length of time to excite any impression, and such impression will continue even after the cause has ceased to act. The length of its duration depends, *cæteris paribus*, on the colour of the light; white lasting longest, next yellow, then red, and last of all blue. The mean duration of the impression excited by all the colours from the instant of their maximum intensity till their entire disappearance is $\frac{1}{3}$rd of a second in a dark room, and $\frac{1}{6}$th of the same time in a light room. If two or more impressions succeed each other at such short intervals that the first has not faded away before the next commences, they run into one another, so that it seems as if the eye received but a single impression from the combination of the individual impressions succeeding each other so rapidly.

Hence arise the many deceptions by which we seem to view an object in rapid motion at several points in its path at once; *ex. gr.*, a flash of lightning appears to us one continued stream of light; a lighted stick whirled round quickly describes, apparently, a continuous circle of fire. Catherine-wheels and rockets, by their rapid movements, produce the impression on our retina of uninterrupted lines of light. On the same principle also we can account for the action of the *Thaumatrope* and of the *Stroboscopic plates*, invented by Stampfer of Vienna, in 1833; also for the effects of Newton's coloured wheels. (§ 324.) If the luminous impression be feeble, and also in rapid motion, it will not be perceived by us; hence musket and cannon-balls fly unseen.

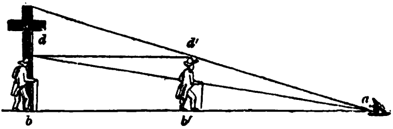
§ 348.

In forming an idea of the real *magnitude*, *distance*, *position*, and *motions* of objects, our judgment performs acts and draws conclusions which have become easy to us by continual exercise from the time of our childhood. It is readily seen how, in arriving at conclusions on these matters, errors frequently arise; also how this faculty may be improved by practice; and, lastly, why little children, and persons who, being born blind, have recovered their eyesight, are deficient in these uses of the organs of vision.

We infer the *real magnitude* of an object from its *apparent magnitude*, or from the angle under which its rays intersect each other in the eye. The extension of that side of an object which is turned towards us is seen under this angle, which is termed the "*angle of vision*," or "angulus opticus." If two objects of unequal magnitudes be at equal distances from us, the greater object will have the greater angle; but if the distances be unequal, it is very possible that they may make equal angles.

Suppose *b c* and *b d*, *fig.* 92., to be two objects at the same distance from an eye, at *a*; *b c* will be seen under a greater angle-of-vision, *b a c*, than *b d* will, its angle being only *b a d*; if *b d* approach the spectator and acquire a new position *b′ d′*, the two objects will then be seen under the same angle.

Fig. 92.



If we call the angle of vision a, the perpendicular height of an object h, and its distance d, then $\frac{h}{d} = \tan. a$; or $h = d \,.\, \tan.\, a$, and $d = h \,.\, \cot.\, a$, which are the mathematical expressions for the true height and distance of an object.

As has been already remarked, we throw back the image of any object formed in the interior of our eye to a certain distance before it. But all that we know as to the actual distance of any object from us is merely a deduction of our judgment, arrived at through the sensations which we find to be excited in the eye according to the different distances of objects. These sensations are regulated —

1.) By the *angle of vision*, when the actual size of the object is known to us.

From the decrease in the magnitude of the optic angle of any object of known size, as *ex. gr.*, a man, we infer the increase of its distance.

2.) From the angle which the axes of the eyes, when directed towards the object, form with it at their point of contact, this angle, called the angle of parallax, becomes greater as the object is nearer.

If an object be at *c*, *fig.* 91., the angle of parallax at this distance is x; but if it recede to l, the angle becomes y, which is obviously less than x.

3.) From the *illuminating power* of the object; as this decreases the distance appears to increase.

The light of the day, the position of the sun, and the clearness of the atmosphere exert a considerable influence on the illuminating power of objects; hence our judgment is frequently misled in estimating the distance of objects.

4.) From *the number of things intervening between the eye of the observer and the object*, since by inductive reasoning from the distances of nearer objects we infer the distances of such as are more remote.

> If, when the distances are considerable, we have no intervening standard of measurement, our conclusions as to the remoteness of objects are often erroneous, and generally we are apt to underrate their distance: this has been experienced by most persons at some time when looking over a wide plane on which there were either few objects, or none at all, to serve as standards of measurement, especially when looking at a sea on which there were but few vessels.

5.) From *the position of the object relatively to some other objects whose distance is known*; in this case we use the known distance as a measure by which to judge of the unknown.

Our estimate of the distance of any object will be increasingly accurate, in proportion to the number of these elements which enter into our calculations. When objects are near to us, nearly all the points which we have been considering act together, and give greater certainty to our estimate. The greater the distance, the fewer of these auxiliaries there are to assist us, until certain limits are exceeded, when nothing remains on which to base our conclusions.

By the same means we determine the *relative positions* of objects to one another. We are principally guided by the angle of vision which the position of objects makes in our eye, *i. e.* by the space which intervenes on the retina between the images the objects produce. When this angle is of an average magnitude, our judgment will generally be most accurate.

We estimate the *motions* of objects by the movement of their images on the retina; to be perceptible, they must have a velocity which will cause the image to describe an arc of one minute in a second of time.

> Motions which produce a smaller change than that named above, in the angle of vision, are not appreciable by us; hence we do not see the hour-hand of a clock move, nor do we perceive the motions of the heavenly bodies.

§ 349.

Those colours are called *accidental* colours which are observed to be but transient on a body, or which continue to be depicted on the retina for a short time after the object which produced the impression has been removed; they are sometimes called *subjective* or *physiological* colours, to distinguish them from such as are permanent to bodies, and which are termed *objective* colours.

They are excited by the external impressions of light, under two distinct conditions, viz. when the eye has been very vividly affected by the action of white or coloured light upon it; and also by the contrast of a colour, when white light succeeds the coloured rays. The phenomenon, in the main, consists in this, that the first vivid impression after some time induces its opposite in the eye; thus white light is succeeded by an *ocular spectrum* of black, and each of the colours is followed by an image of its complementary colour.

Instances of ocular spectra induced by intense luminous excitement: —

First Expt. Look steadfastly with both eyes upon a black figure (a wafer), on a white sheet of paper, on which the sun shines strongly; and then hold a handkerchief over your eyes, or turn towards a greyish or dimly illuminated wall; and you will have the impression of a white wafer on a grey ground. The converse obtains, if a white object be looked at, on a black surface.

A similar effect is produced, if a person look steadily for some time through a window, at white clouds; and then cover his eyes with a bandage, he will have a spectrum of dark clouds behind white window frames.

Second Expt. Lay any coloured object, as a red wafer, or, better still, a piece of red ribbon, on a sheet of paper, and look at it till the eye becomes weary with counting the threads; if the ribbon be removed quickly, a spectrum of green, the complementary colour to red, will be seen.

Dr. Böttger observed, that when a plate of white porcelain was substituted for the sheet of paper, in this and the preceding experiment, the accidental colours were rendered much brighter and purer.

Third Expt. Burn a small quantity of red fire in a dark room; extinguish it, and the eye will see a green flame. If the eye be closed, the green spectrum will be equally visible as if it be kept open. The succession of the colours will be inverted, by burning something that will produce a green light. A similar effect follows, if the setting sun be long and steadily looked at, its red disc being succeeded by a green spectrum.

That these colours are accidental, may be inferred from the fact that, if one eye be closed, whilst the other receives the impression from the light, the phenomenon takes place only in that eye, and not in the closed one.

Fourth Expt. If we look long at an object through a coloured glass, for instance, through a piece of violet glass, the object will seem to be illuminated by the sunshine.

Experiments on ocular spectra by contrast: —

Fifth Expt. Coloured Shadows. — Make two apertures, in the form of parallelograms, in a window shutter, the width of the holes being 4 to 6 inches, and their distance asunder, measured horizontally, from 1½ to 2 feet. Close one of the apertures with a stained glass plate, and the other with a wooden slide. Allow a coloured beam, through the first opening, to fall upon a rod, and it will project a black shadow on a white screen placed behind it; the rest of the screen being apparently of the same colour as the glass through which the light was admitted. In like manner, admit only white light through the other opening, and the rod will cast a black shadow on a white ground. Now, if light be admitted simultaneously through both the apertures, the rod will cast a shadow from each of the sources of light; but both of them will be coloured, instead of being black, as before; the shadow projected by the day-light being of the same colour with the stained glass, whilst the shadow cast by the coloured light, and partially illuminated by the sun's rays, exhibits the complementary colours. Thus, by means of a green plate, we get green and red shadows; by an orange plate, orange and blue shadows, &c. The size of the aperture by which day-light is admitted may be regulated by the wooden slides.

Coloured shadows may be obtained in a still more simple mode, thus: admit day-light through a small opening into a room, and project the shadow of any opaque object upon a white screen. Place a lighted candle or lamp at a proper distance from the body, and it will cast a second shadow; the former shadow becoming orange-coloured, and the latter blue. The shadow cast by the day-light is rendered orange by the orange rays of the artificial light; whence the shadow which it casts necessarily appears of the complementary colour.

Sixth Expt. Spectrum of Complementary Colours by Double Reflection. —Lay a plate of coloured glass on a common looking-glass; if a small space, about a ¼ of an inch, be left between the two surfaces, it will be better. Interpose between the plate and the looking-glass a sheet of black paper, so that the under-surface of the stained glass may not reflect the light; hold a sheet of white paper, on which a black figure is marked, in front of the glass; and the drawing will be reflected the same as in an ordinary looking-glass: that is to say, the white will appear white, and the black, black. If the black paper be removed, we shall have a double image —one reflected from the surface of the coloured glass, and the other from that of the looking-glass. Take away the black paper, the light will pass through the coloured glass, which we will suppose to be green; the under-surface will accordingly reflect a green image; and the upper one, which before threw back a white image, will now reflect one of the complementary colour, red. If a yellow or blue glass be substituted for the green, corresponding results will follow.

The explanations hitherto given of these phenomena are as numerous as they are unsatisfactory. That of Petrini is the simplest and most natural. Every nerve, he says, becomes fatigued by an impression continuing long upon it; and every less powerful impression fades away, or is received less vividly, when accompanied by one more powerful. When, therefore, the eye has received a very powerful impression from any coloured light, the sensation of this colour disappears from the more feeble white light, and the complementary impression alone remains. In short, if the eye is affected by any predominant colour, it immediately receives the sensation of its complementary colour, just as when a string is struck, the ear perceives simultaneously the fundamental note and the note that harmonizes with it.

XI. THE PRINCIPAL OPTICAL INSTRUMENTS.

1). *The Camera Obscura.*

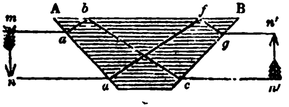
§ 350.

The *Camera Obscura*, as its name imports, is a dark chamber, enclosed on all sides: as generally constructed, it is a box, painted black inside; the light from external objects being admitted into it through a convex lens, which, collecting the rays transmitted through it, forms an inverted image of these external objects (§ 314.) at the focus where the refracted rays meet: the image thus produced is received on a white screen.

To obtain an erect vertical image, according to Horner, we should use a right-angled prism, which will refract a second time, and in an inverted position, the rays transmitted through the convex lens.

Let A B C, *fig.* 93., represent the prism, and *m a*, *n d* two rays which have passed through the convex lens and produce the inverted image *m n*; then, as the diagram shows, *m a* is refracted in the direction *a b c m'*, and *n d* in the direction *d f g n'*; whence it follows that *m' n'* must be an inverted image of *m n*.

Fig. 93.



If we wish to obtain the image on a horizontal plane, we should make use of a plane mirror, inclined at an angle of 45° to the axis of the lens; by which means the rays, after passing through the lens, will be reflected either upwards or downwards. In the first case, the image is generally received on a plate of ground glass, through which it shines so as to be visible from above. This apparatus is sometimes called a *camera clara*. In the second case, a sheet of white paper is usually placed to receive the image horizontally, the mirror being made to reflect the rays downwards, instead of upwards; the spectator must, in this arrangement, either be himself within the camera, or he must look in upon the images through a small round hole, made for this purpose, in the side of the instrument.

The images formed by the camera obscura depict most accurately the forms, colours, and degree of illumination belonging to the different objects; it has the additional charm of presenting us with an animated picture, the movements of external objects being repeated in the image. It represents, on an enlarged scale, what is continually taking place on the retina of our eyes.

> Why are not the images of near and distant objects presented to us with equal distinctness by the camera? — How can we adjust the instrument for distinctly representing objects at different distances? — If the image formed by the convex lens is received on a convave instead of on a plane surface, the whole picture will be rendered distinct. Why? — Advantages derived from the use of an achromatic convex glass. — Why is a metallic speculum preferable to the common looking-glass, generally used in this instrument?
>
> The camera obscura was invented in the 16th century, by John Bap. Porta. Wollaston's camera lucida is now more generally used than the former instrument, to obtain mechanically correct representations of natural objects.

2.) *The Different Kinds of Microscopes.*

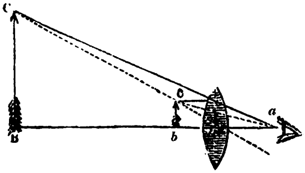
§ 351.

The use of a microscope is to furnish us with magnified images of objects so minute, that when held at the distance of distinct vision, the eye would be incapable of distinguishing their form and parts. This is accomplished by enlarging the optic angle; for every object appears greater according as we increase this angle; greater, consequently, as we bring it nearer to our eye (§ 348.): but we cannot bring an object nearer than the distance of distinct vision, *i. e.* within from 8 to 10 inches of the eye; for if we do, the angle of vision and the image of the object become so enlarged, that the image is projected beyond the retina, and is of necessity indistinct.

> *Expt.* Prick a card with a fine needle, and placing yourself before a window, look through the puncture at a needle, which must be held at the distance of distinct vision, and in a line with your eye: you will observe that the image of the needle is considerably magnified the nearer it is brought to the aperture in the card, till, when it is close to it, the outline of its eye becomes altogether indistinct.

The *single microscope* consists of a convex lens, with a very short focal distance. If an object be viewed through it at less than its focal distance, but near to the focus, the rays transmitted through the lens will be rendered more convergent, and an eye on which they fall will see the object under a greater angle of vision, *i. e.* it will see the object magnified.

Fig. 94.



> An eye *a*, *fig.* 94., would see the object *b c* under the angle *b a c*: interpose between the eye and the object a convex lens *m*, at the proper distance, and the rays will be refracted (§ 311.), as shown in the *fig.*, so that the object will be viewed under the larger visual angle B *a* C; the object itself will, therefore, appear magnified as B C.

The image of an object produced thus will be thrown back by the eye to the distance of distinct vision, viz. to 8 or 10 inches from it. A short-sighted eye would require that the object should be brought nearer to the glass, and a far-sighted person would place the object further from him; it would, therefore, appear more highly magnified to the latter than to the former. The linear magnifying power of such a lens will be nearly the multiple that the distance of distinct vision is of its focal length.

> We have said above, that the distance *b m*, *fig.* 94., at which the object *b c* is to be placed before the lens, must be nearly equal to its focal length in order to obtain from it the greatest possible magnifying power; let B *m* be the dis-

tance of distinct vision, at which the magnified image B C appears to the eye; then, because the Δs $b\,c\,m$ and B C m are similar,

$$\mathrm{B\,C} : b\,c = \mathrm{B}\,m : b\,m,$$

$$\therefore\ \mathrm{B\,C} = \frac{\mathrm{B}\,m}{b\,m} .\ b\,c.$$

Now let the size of the object $b\,c$ be 1, its distance from the optical centre of the lens $b\,m$, which is very nearly the same as its focal distance f, the distance of distinct vision $\mathrm{B}\,m = v$; then the magnifying power m would be thus expressed, $m = \frac{v}{f}$; *i. e.* it would equal the distance of distinct vision divided by the focal length. The magnifying power rather exceeds this quotient. In fact, we have to imagine the eye as seeing the image produced by the refraction of the lens at the distance of distinct vision, as if it were a virtual image on the same side of the lens with the object itself. Then from the mathematical deductions appended to § 312., if $b\,m$ = the distance of the object from the optical centre m, $\mathrm{B}\,m$ = the focal length, or distance of the image from m; then by equation 1.

$$\frac{1}{f} = \frac{1}{a} + \frac{1}{a}\text{: or, in this case, }\frac{1}{f} = \frac{1}{b\,m} + \frac{1}{\mathrm{B}\,m}.$$

But as the image which the eye perceives has a position exactly opposite to that which it is assumed to have in the above equation, a or $\mathrm{B}\,m$ must be made negative; hence:

$$\frac{1}{f} = \frac{1}{b\,m} - \frac{1}{\mathrm{B}\,m};$$

or

$$\frac{\mathrm{B}\,m}{f} = \frac{\mathrm{B}\,m}{b\,m} - 1,$$

and

$$\frac{\mathrm{B}\,m}{b\,m} = \frac{\mathrm{B}\,m}{f} + 1.$$

If now we substitute the values assumed above, we get

$$m = \frac{v}{f} + 1.$$

Supposing that the eye is placed as near as possible to the lens, the thickness of which may be neglected, it follows that the number expressing the linear magnifying power of the microscope exceeds by 1 the quotient obtained by dividing the distance of distinct vision by the focal length.

With this correction then, a lens having a focal distance of 1 inch will have a magnifying power of 9 for an eye whose distance of distinct vision is 8 inches, of 10 for an eye whose distance is 9 inches, of 11 for an eye whose distance is 10 inches. Consequently, a lens will magnify objects 21 times if its focal distance be ½ an inch, and the distance of distinct vision be 10 inches; if the focal distance be ¼ of an inch, it will magnify 41 times; if $\frac{1}{10}$th of an inch, 101 times. It must be remembered that in all these instances we speak only of linear magnifying power. The superficial magnifying power is found by squaring the linear.

§ 352.

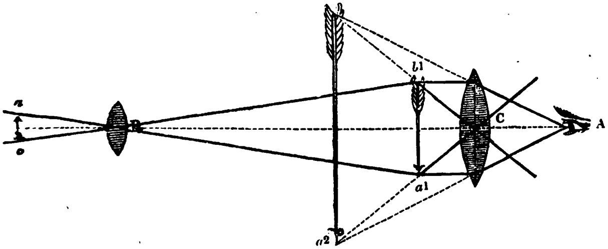
The *compound microscope* consists of several convex lenses, or of a combination of concave specula and lenses. The former is termed a *dioptric* or *refracting*, and the latter a *catoptric* or *reflecting microscope*.

In its simplest form, the refracting microscope consists of only two convex lenses. The lens nearest to the object is called the *object-glass*, and has a very short focal length. The object to be examined is placed beyond the focal length, but near the focus of this lens, which forms a magnified but inverted image of the object on its further side. (§ 311. 5.) The second convex lens, called the *eye-glass*, has a greater focal length than the other. Its axis coincides with that of the object-glass, beyond which it is placed at such a distance, that an eye looking through it sees an inverted image of the object, just like that viewed in a single microscope. The linear magnifying power of these microscopes is equal to the product of the magnifying powers of the two glasses.

In reflecting microscopes the place of the object-glass is occupied by a concave speculum, which produces an inverted image also. (§ 295. 4.)

Fig. 95. illustrates the principle on which compound microscopes act. — *a b* is the object, B the object-glass,

Fig. 95.



a′ b′ the magnified inverted image formed by this lens, and

$a^2 b^2$ the image magnified again by the eye-glass C, and seen by the eye at A under the angle of vision a^2 A b^2.

If we suppose the magnifying power of the object-glass to be 20, so that $a' b' = 20\, a\, b$, and that of the object-glass 5, so that $a^2 b^2 = 5\, a' b'$, $a^2 b^2 = 20 \times 5 = 100\, a\, b$; or, in other words, the eye will view the object under an angle 100 times larger than it would have done unaided by this instrument. — The superficial magnifying power is found in the same manner as that of single microscopes.

Dr. August gives the following method of testing pretty nearly the magnifying power of one of these microscopes. Place some object of known size before the object-glass, look with one eye through the microscope, and with the other at the point of a pair of compasses which you hold at the distance of distinct vision before the other eye. Open the legs of the compass to such a distance as equals the diameter of the object viewed through the microscope. Divide this diameter by the actual diameter of the object, both being in the same denomination, and the quotient will give the magnifying power required.

Advantages derived from the use of achromatic object-glasses. — Microscope with more than two convex lenses. — Campani's collective lens.

§ 353.

The *solar microscope* is nothing more than a magic lantern, the light of the sun being used instead of that of a lamp. The object to be magnified is strongly illuminated, and its inverted image, formed by a convex lens of short focal length, is projected on a white screen: the object is to be placed near but a little beyond the focus. The rays of light which pass through the lens are so refracted by it (§ 311. 5.) that they form an inverted image at a certain distance from it; which distance and image will be greater, the nearer the object is to the focus. The linear magnifying power is proportional to the distance of the image from the lens divided by its focal length, or it equals the diameter of the image divided by that of the object. If the light be sufficiently strong, a more brilliant image will be obtained than from the common microscopes.

Lately, for the light of the sun, or of a lamp, there has been substituted the intense light generated by the combustion of a piece of lime in a stream of oxy-hydrogen gas, whence the instrument is called the *oxy-hydrogen microscope.* The intensity of this light is such that a cylinder of the ignited lime half an inch in diameter diffuses a light greater than that yielded by 153 wax candles. — To illuminate the object sufficiently, a convex lens is used of considerable size to refract the rays of the sun, lamp, or ignited lime, so that they may fall together on the object. This lens is called a *collective* or *illuminating lens.*

3.) *The Different Kinds of Telescopes.*

§ 354.

Telescopes are used for much the same purpose as microscopes, viz. to present objects to our eye under a greater visual angle, and consequently with their proportions enlarged. The difference in the application of the two classes of instruments is, that telescopes serve to magnify objects that appear small from their great distance, whilst microscopes are used to magnify minute objects near us.

Telescopes are either *refracting* telescopes, and consist entirely of lenses combined together, or of lenses and concave specula when they are said to be *reflecting* telescopes.

Telescopes, like microscopes, magnify objects by enlarging the angle under which they are viewed. Their power equals the quotient of the visual angle of the eye looking through a telescope divided by the visual angle of the naked eye.

The space or range seen through a telescope is technically termed the *field of vision.* It is measured by dividing the angle under which it is seen by the angle of vision of the naked eye embracing the same field within its view: the greater the magnifying power of the instrument, the less will the angle of vision of the naked eye be compared with that of an eye looking through the glass.

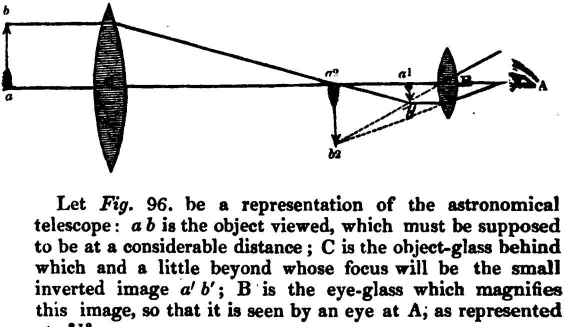
It is requisite that the objects viewed through a telescope should be seen with the greatest possible *distinctness,* and that they should appear as strongly *illuminated* as possible. Now, the combination of these two essential properties is not very easy; for, to admit a large quantity of light into the tube we must enlarge the dimensions of the lenses, whereas to obtain distinct images it is needful to use lenses of the smallest available size. The object aimed at in the construction of telescopes is therefore to secure the greatest attainable distinctness of the image consistent with the admission of an adequate degree of light.

§ 355.

Refracting telescopes are of three kinds, viz. Keppler's, or the *astronomical telescope,* invented by Keppler, 1611; the *terrestrial,* invented by the Jesuit Maria de Rheita, about the year 1630; and the *Dutch* telescope, or Galileo's telescope, first made by Jansen in 1590. The two first are merely combinations of convex lenses, the last consists of both convex and concave lenses.

The *astronomical* telescope is made by placing two convex lenses of unequal focal lengths one before the other, in such a manner that they may have a common axis. The farther lens is termed the *object-glass;* it forms an inverted image of the objects seen through it; if they be very distant the image will be near the focus of the glass, and in proportion as their distance diminishes the image recedes from the focus. (§ 311. 1, 2, and 3.) The observer views this image through the second or *eye-glass*, in the same manner as through a single microscope: the image will therefore be seen by him under a greater optic angle, and consequently it will be magnified, but will still be inverted. — From this explanation the similarity in construction and in principle of these telescopes and of compound microscopes is evident. — The lenses are generally distant from each other a space equal to the sum of their focal lengths; but if less distant objects are viewed through the instrument, the lenses must be adjusted for a wider distance, that the image formed by the object-glass may fall beyond its focal length. — The magnifying power is found by dividing the focal length of the object-glass by that of the eye-glass.

Fig. 96.



Let *Fig.* 96. be a representation of the astronomical telescope: *a b* is the object viewed, which must be supposed to be at a considerable distance; C is the object-glass behind which and a little beyond whose focus will be the small inverted image *a′ b′*; B is the eye-glass which magnifies this image, so that it is seen by an eye at A; as represented at $a^2 b^2$.

Suppose the object-glass to have a 10 inch focal length, and that the eye-glass has only 1 inch, then the instrument magnifies an object seen through it 10 times; if the object-glass have a 100 inch focal length, the same eye-glass would magnify an object 100 times; if we substitute an eye-glass with a focal length of ½ an inch, then the magnifying power would be 200 times.

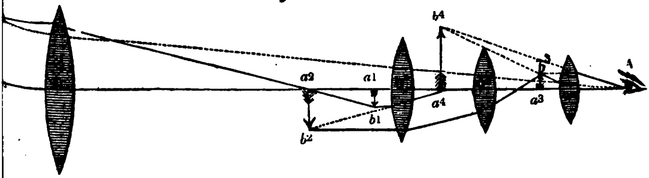
As its appellation indeed shows, this instrument is used principally in making astronomical observations; for which purpose the inversion of the images is of small consequence. Its advantages are, that with an entensive field of vision it admits a large quantity of light, and possesses higher magnifying power than the other telescopes.

The *night-glass* resembles the astronomical telescope; it differs from it in this, that it has an object-glass of wider aperture and shorter focal length; by which arrangement its magnifying power is less than that of the astronomical telescope, but it presents a wider field of view, admits more light, and consequently shows objects more distinctly. It is serviceable in bringing a larger portion of the heavens under observation by night, and in detecting such heavenly bodies as have but feeble illuminating powers.

The *terrestrial telescope* consists of at least four convex lenses; it may therefore be regarded as a double astronomical telescope, all the glasses having a common axis. The inverted image formed by the object-glass of the anterior astronomical telescope is again inverted and magnified by the posterior telescope, and is therefore presented erect to the eye of the observer. As these instruments present objects in their natural position, they are used chiefly for viewing distant objects on the surface of the earth; and hence their name. Like the astronomical telescope they have a large field of sight; but in consequence of the repeated refraction of the light it becomes much diminished, so that objects cannot be as much magnified in them, as in the astronomical telescope, without the distinctness of the image being impaired.

The terrestrial telescope is represented in *fig.* 97. L is the double convex object-glass, of great focal length; o^1, o^2, o^3

Fig. 97.



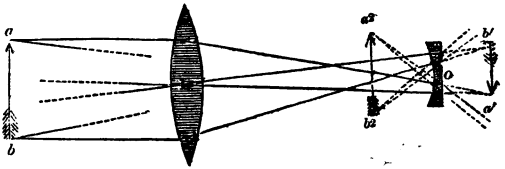
are three double convex eye-glasses, of shorter but equal focal distances, set in one tube, so that the posterior focus of one eye-glass may coincide with the anterior focus of the next. These foci are marked on the axis *a* A. For use, the instrument must be so adjusted that the object-glass L shall project the inverted image *a′ b′*, which it forms a little beyond the anterior focus of the first eye-glass. If an observer were to look through this glass, he would perceive an inverted magnified image a^2 b^2, precisely as in the astronomical telescope. Now, this image being beyond the focal distance of the second lens, o^2, an erect reduced image is formed within the focal length of the third lens, o^3, which is viewed by an eye at A looking through this last eye-glass as through a single microscope, in the position a^4 b^4. This last image will be magnified, because it is seen by the eye at the distance of distinct vision, under the enlarged angle a^4 A b^4.

The field of sight, in both these kinds of telescopes, may be enlarged by placing an illuminating lens before the proper eye-glass; the distinctness of the image will not be impaired by this addition. We have remarked before, that the field of a compound microscope is enlarged by the same contrivance.

The *Galilean telescope,* which, when made on a small scale, is termed an opera glass, consists of a convex object-glass and a concave eye-glass. They are placed asunder, at a distance equal to the difference of their focal lengths, and, like the terrestrial telescope, present objects to our view in an erect position. The object-glass would form an inverted image beyond its focus, did not the concave eye-glass receive the convergent rays before they meet and form the image, and, by refracting them, causes these rays to diverge; the image will consequently be seen in an erect position, between the two lenses. The magnifying power of these telescopes is found by dividing the focal length of the object-glass by that of the eye-glass.

Fig. 98. represents the combination of these two lenses, and the consequent refraction of the rays of light produced in a telescope of this kind. Let a b be an object supposed to be at a great distance from the observer; L is the convex object-glass; b' a' is the inverted image which would be formed, but for the interposition of the lens o, which, by refracting the rays before they reach this point, causes them to diverge and form the erect image a^2 b^2.

Fig. 98.



Since these telescopes have, in common with the terrestrial telescopes, the convenience of representing objects to us in their erect position, they are generally used in observing objects at the surface of the earth. In consequence of the dispersion of the light by the concave eye-glass, they afford but a limited field, and are incapable of magnifying objects to a high degree. On the other hand, they are the shortest and most portable telescopes, from the position and short focal lengths of their lenses; if their glasses are good, they give distinct and clearly defined images of objects; and, at the same time, considerably enlarge their proportions.

§ 356.

The common and older telescopes of all the three varieties which we have just described, have one defect in common, viz. that, owing to the spherical forms of the object glass (§ 309.), and its dispersive property (§ 319.), images viewed through these instruments were never seen distinctly, and their edges were invariably tinged more or less, according to the convexity of the object glass: the more the dimensions of the telescope were reduced, the more these defects were aggravated. Attempts were made to obviate the former of these inconveniences, by using object-glasses of great focal lengths; and the latter was reduced, by covering part of the glasses with a rim or blind, the prismatic dispersion being greatest at the edge of a lens. Without altogether perfecting the instrument, it was rendered cumbrous, and besides lost much light.

The discovery of achromatic lenses, by Dolland (§ 322.), supplied a method for freeing telescopes from these imperfections; by merely fitting them up with achromatic object-glasses. These telescopes are superior to the common ones in the following respects: that—

1.) They represent objects very distinctly, and quite free from prismatic colouring on the edges.

2.) As the rim, or blind, by which a part of the surface of the lenses in the other telescopes was covered, is altogether dispensed with in the achromatic telescopes, their field of sight is larger; and—

3.) Their magnifying power is as great as that of longer telescopes, made on the ordinary plan.

The largest and best achromatic telescopes are those which have been executed in the manufactory of M. Fraunhofer at Munich. The instrument made for the observatory at Dorpat has an achromatic object-glass, 9 inches in diameter, and 160 inches in focal length; this telescope magnifies objects 700 times; it is fitted up with a parallax apparatus, so that when it is directed towards any star, it is retained, by means of a piece of clock-work, in such a position, that the star is kept in the centre of the field of vision. A refracting telescope, of still larger dimensions, was set up at the observatory at St. Petersburg.

Achromatic telescopes are very expensive, chiefly because flint glass can rarely be obtained of large size, and at the same time free from flaws. Prof. Littson of Vienna, in 1827, suggested a method, by which small flint glass lenses might be rendered equally efficacious with large ones. He proposed that the telescope should be fitted up with its proper object glass of crown-glass; and that a flint glass lens, of much smaller diameter, should be placed at a proper distance behind the former, to counteract the prismatic dispersion of the rays. The name of *dialytic telescopes* was given to these instruments. Plössl, of Vienna, was the first who succeeded in constructing one to work accurately.

§ 357.

The principal difference between the telescopes already described and the *reflecting* telescopes is, that in the latter a metallic speculum is used, instead of the convex object-glass of the former. The inverted image formed by the speculum (§ 295.) is viewed through a refracting eye-glass by which it is magnified.

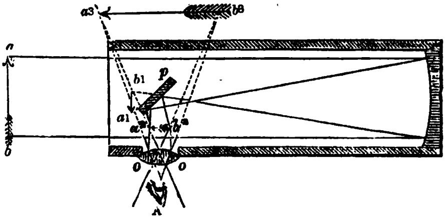
As reflection from specula is unaccompanied with any prismatic dispersion, these telescopes were superior to all non-achromatic telescopes in this, that they produced images free from colour. The inaccuracy of the image, too, arising from spherical aberration (§ 293.), could be done away with by using a speculum of parabolic form. Their defects were, that the specula absorbed more light than lenses; they lost the correct curvature of their surface more readily than lenses their distinctness; and also, that the manipulation of reflecting telescopes was found to be less convenient than that of refracting telescopes.

Reflecting telescopes were invented towards the close of the seventeenth century; thus, until achromatic telescopes were made, they were the only ones free from the faults mentioned above; and, consequently, they were the best adapted for astronomical purposes.

The mode in which they were constructed varied, and the images formed by them might be either erect or inverted. The following are the chief varieties:—

The oldest, or *Newtonian telescope*, was constructed thus: referring to *fig.* 99., S, will be the metallic speculum, which would give an inverted image $a' b'$ of an object $a b$ opposite to it.

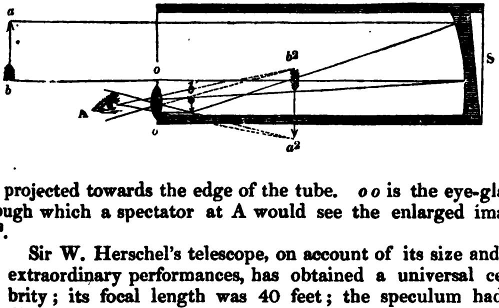
Fig. 99.



The plane mirror *p*, placed so as to receive these rays at an angle of 45°, threw them back, and formed the second image $a^2\,b^2$. *o o* is merely a convex eye-glass, which refracted the rays of the image $a^2\,b^2$ in such a manner, that an eye at A would have an enlarged image $a^3\,b^3$.

In *Herschel's telescope* (*fig.* 100.) the metallic speculum, S, is set at such an inclination to the axis of the tube which contained it, that the inverted image *b′ a′*, which it formed of an object *a b*,

Fig. 100.

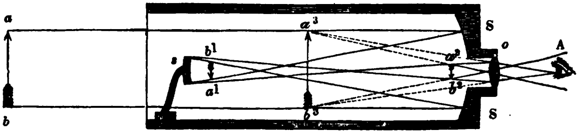


was projected towards the edge of the tube. *o o* is the eye-glass, through which a spectator at A would see the enlarged image $a^2\,b^2$.

Sir W. Herschel's telescope, on account of its size and its extraordinary performances, has obtained a universal celebrity; its focal length was 40 feet; the speculum had a diameter of 4 feet; and its weight, when cast, was 2118lbs. It magnified objects nearly 7000 times, and brought 36,500 times as much light into the eye as would have been derived, without such aid, from the object.

A third kind of reflecting telescope is that called the *Gregorian*, which is made thus: — S S, *fig.* 101, is the speculum; *b′ a′*, the inverted image formed by it, of the object *a b*. This image is reflected again by a second small concave speculum, *s*, placed before the great speculum, and in its axis; and thus it forms the

Fig. 101.



erect image $a^2 b^2$, which, to an eye at A, will be magnified into $a^3 b^3$. This form of telescope is superior to the other two, inasmuch as, in making observations, it can be directed towards the object in the direction of the line of sight; and next, that objects viewed in it are presented in an erect position. The disadvantages connected with it are, that the quantity of light is diminished, and the objects are seen less distinctly, in consequence of the aperture made in the middle of the object speculum.

As the owners of telescopes may perhaps wish to be able to estimate their magnifying power, and the extent of their field of vision, it may be worth while to give the following method as described by Dr. August: —

The *magnifying powers* may be estimated pretty nearly by looking at the same object with one eye through the telescope and with the other naked, and comparing the apparent magnitudes of the two images. This measurement may be rendered still more exact if any kind of telescope, except a Galilean, be pointed towards a clear part of the sky, and a leaf of thin paper or transparent horn be held behind the last eye-glass, at the spot where the eye is ordinarily placed; a bright, strongly-defined luminous circle will be visible on the transparent plate, supposing it to be held at the right spot. Measure its diameter as accurately as possible, and then measure the width of the object-glass, using the same scale in each case, divide its diameter by that of the luminous spot, and the quotient will give the magnifying power of the telescope.

The luminous circle is, in fact, an image of the object-glass itself, whence it may be proved that it is contained in the diameter of the object-glass as many times as are equal to the magnifying power of the telescope. The object-glass may be taken out, and a rim, or annulus, having exactly the same opening as will be equal to the circle of light, put in its place; the quantity of light will be increased, and the images of objects rendered more distinct by this alteration. — Ramsden contrived a little instrument, to which he gave the name of *Dynamometer*, for measuring the powers of telescopes.

The *field* of a telescope may be estimated by comparing its diameter with the apparent diameter of some object viewed through the telescope. In the choice of an object, one should be selected whose apparent diameter is already known to us; that of the sun or moon will answer the purpose well; they are both equal, or very nearly so, the apparent difference amounting only to half a degree, or 30 minutes.—Or, the field may be measured by directing the telescope to some star in or very near to the equator, care being taken that it shall pass over the *middle* of the field, and then count the number of seconds which elapse during its passage: four seconds of time will make an angle of one minute for the field of vision.

XII. THE THERMAL, CHEMICAL, AND OTHER NON-OPTICAL EFFECTS OF LIGHT.

§ 358.

All the phenomena of light which we have hitherto noticed are of a purely optical nature, *i. e.* they are such as act only on our organs of vision. Light, however, is an active agent in bringing about quite another class of phenomena; it excites *heat* and *electricity;* on most bodies it exerts a *chemical* influence, and displays a vivifying power in its operations on organic matter; whether it possesses *magnetic* properties is a matter of doubt.

As to the excitation of heat, it has not yet been proved that this property is possessed by all sources of light, though it is known that the sun's rays have it in a high degree: it appears to stand in a direct ratio to the intensity of the illumination and the absorptive power of the body. The heating powers of the differently coloured solar rays are extremely unequal, the greatest heat being found to exist near to, but slightly beyond, the red rays in the solar spectrum, their respective heating powers decreasing till we arrive at the violet, where this property ceases altogether. A more detailed explanation will be found in the CHAPTER ON HEAT.

The *chemical properties* of light are shown in this, that the light of the sun, and, in an inferior degree, that of day when the sun is hid from our view, is a means of accelerating chemical combinations and decompositions. Thus, as we have already mentioned, the rays of light seem to carry with them both thermal and chemical rays; the maximum intensity of the former spectrum coinciding with the red rays, whilst the maximum of the chemical spectrum is found in the violet light and a little beyond, its intensity diminishing gradually throughout the other colours till its effects entirely cease at the red.

Besides the chromatic spectrum produced by the passage of light through a prism, the greatest intensity of which is found in the yellow, there exists a thermal spectrum whose maximum coincides nearly with the red, and a chemical spectrum having its maximum in the violet; these last two spectra have their maximum and minimum points at opposite ends of the spectrum; *i. e.* the greatest heating power resides where the chemical power is feeblest, and *vice versâ.* This is represented graphically in *fig.* 69., the faint line being the curve of luminous, the dark line that of thermal, and the dotted line that of chemical intensity.

According to the undulatory theory it would follow, that the æther acquires its greatest heating power when it vibrates least rapidly, and its greatest chemical power when its undulations become the most rapid.

As far as experiment has hitherto shown, the chemical influence of light is more often displayed in decomposing than in combining substances; the nature of this influence we are not precisely acquainted with, but its existence is evident from the change light produces in the colours of bodies, generally rendering them more pale after exposure to its action.

These chemical rays penetrate both opaque and transparent bodies, but in different degrees, as the experiments of Biot and Malaguté have satisfactorily proved; no definite relation has yet been detected as subsisting in the chemical constitution of the substances which allow the transmission of these rays. A remarkable distinction is observable in this respect between water and air, the former medium giving to the chemical rays a more free passage than the latter, and consequently retarding the chemical influence.

The chemical agency of light, which has been thus glanced at in general terms, is a subject which, if followed out in all its bearings, would require considerable research in determining the amount of its influence on other physical agents. A few only of its best known effects can here be noticed.

Chemical combinations brought about by the agency of light are to be found principally among the gases. Chlorine combines most readily in white light, and especially in that of the sun, with hydrogen, carburetted oxygen, and with organic substances, from which it generally withdraws their hydogen.

Light is recognized as a powerful agent in effecting chemical decomposition, chiefly among the easily reducible oxides of the perfect metals (§ 72.), either with or without the presence of other agents, as formic acid, phosphorus, carbon, &c. The most general effect of this kind is the blackening of the salts of silver, which has, with great probability, been supposed to be a partial reduction. The decomposition of nitric acid through the agency of light has been long known; this acid, when exposed to the beams of the sun, is soon resolved into oxygen and nitrous acid. Light brings about similar decompositions of several of the super-oxides.

It has not yet been decided whether or no the loss of colour sustained by vegetable dyes through the action of light is owing to a species of oxidization: the bleaching of some kinds of wove goods is facilitated by exposure to light.

The following experiments may serve to prove the chemical influence of light: —

First Expt. Place a mixture of equal parts (by measure) of chlorine and hydrogen gas in a glass vessel, and no change will happen, if the vessel be kept in the dark, and at an ordinary temperature; but on exposing it to the day-light, the elements will slowly combine, and form hydrochloric acid; if the glass be set in the sun's rays, the union will be accompanied with an instantaneous detonation. The report may also be produced by transmitting ordinary day-light through violet or blue glass on to the mixture. By interposing a red glass between the vessel and the light all combination of the elements is prevented.

Second Expt. In an aqueous solution of chloride of gold place a stick of pure phosphorus so as just to touch the surface of the liquid; a piece of charcoal just extinguished may be used instead of the phosphorus; expose both the solid and the liquid to the action of the sun's rays, and after some time the former will be regularly coated with the metal.

Third Expt. Place in the sunshine a bottle, partly filled with concentrated nitric acid; after some time the acid will become of a yellow colour, and the rest of the bottle will be filled with a yellowish orange vapour, which is nitrous acid. The same result is obtained, by exposing the bottle to the daylight, even without the shining of the sun; or by causing only the blue rays to fall upon it. If the acid be kept in the dark, no change takes place in its composition; nor is it altered, if only the red rays be permitted to fall upon it.

Fourth Expt. The green tincture obtained by extract of the green parts of vegetable substances, as the leaves of cherry and elder, with spirit of wine, on exposure to the light loses its colour.

The yellow powder of gum guaiacum, or paper stained with a tincture of this gum, obtained by dissolving it in alchohol, acquires a green colour, if exposed to either white or blue light; but no change follows, if the red rays of the spectrum fall upon it. Wollaston says that red light will restore the paper to its original yellow, after the other colours had converted it into green.

Fifth Expt. White chloride of silver, drawn in a moist state over paper, becomes at first violet, and afterwards black, on exposure to the light; this change in colour happens more rapidly, and is deeper, according to the intensity of the light. A similar result follows, on exposing the chloride of silver itself to the light. Fasten a piece of paper, prepared in the manner described above, with chloride of silver, behind a semi-transparent picture, on a plate of porcelain; hold the plate to the sun's rays, and according to the intensity of the light, and the length of time the picture is exposed, an image, more or less distinct, will be produced on the paper, the shading of which will be exactly the converse of the original.

These chemical effects of light have recently been made use of to render permanent the images obtained by means of convex lenses; the art of thus fixing them is termed *Photography* or *Heliography*. The mode in which the process is performed is essentially as follows; minor details must of necessity be passed over:—The picture, formed by a very good camera obscura, is received on a plate, whose surface has been prepared so as to render it as susceptible as possible of the chemical influence of light. After the lapse of a longer or shorter time, the light will have so acted on the plate, that the various objects whose images were projected upon it will appear, with all their various gradations of light and shade, most exactly depicted in black and white, no colour being present. The plate is then subjected to certain manipulations, by which the picture is indelibly set.

The essential point in Daguerre's method was the discovery that iodide of silver is extremely sensitive to the chemical action of light; that it is capable of forming an amalgam with the vapour of mercury; and that when a plate has been thus prepared, the images formed on it by the action of light will continue for a length of time. The advances made in this department of practical science since 1839, the date of Daguerre's original discovery, consist, principally, in imparting to the silver plate a still higher degree of sensibility, by the application of chloride of iodine, chloride of bromium, and bromide of iodine. To such perfection has the art been carried that, according to the intensity of the light, one, or a few seconds at most, suffice to fix the images. Daguerre's subsequent discovery is very interesting—that a maximum sensibility is attained by isolating and electrifying the plate; such, indeed, that one-tenth of a second is now a sufficient time to obtain the requisite luminous impression for the formation of the picture. Besides thus increasing the delicacy of the plate, Edmund Becquérel has discovered that the passing of the plate over the fumes of mercury is not necessary; but that the permanency of the picture may be secured as effectually, by submitting it to the secondary action of red, orange, yellow, and green light, after the primitive chemical excitation by the white light.

Universal experience proves that light is a principal source of all organic life; its influence is shown in the tendency of all plants to direct their branches, leaves, and buds to that quarter from which they derive the greatest flood of light. Their varied colours are mainly owing to the action of light upon their leaves. Vegetables grown in dark places are either white, or of a palish yellow. The sunny side of fruits is of a richer tinge than the shady side. Light is not less influential in its bearings on animal life; the hue of the human skin is in great measure attributable to the action of the sun; and men whose daily employment keeps them much within doors are pale and more or less sickly, in consequence of such confinement.

Lastly, with regard to the electrical and magnetic influence of light, as far, at least, as modern research has yet carried us, they are extremely feeble; and, indeed, it is a matter of doubt whether these influences are not altogether of a secondary nature. These alleged discoveries will be referred to more at length in those parts of this work which treat of electricity and magnetism.

SECTION II.

HEAT.

1. THE EFFECTS OF HEAT IN GENERAL.—SENSIBLE AND LATENT HEAT.

§ 359.

The feeling of *touch* is capable of being peculiarly excited by *heat*, as our sense of hearing is excited by sound, and our organs of vision are affected by light. Heat is an agent which performs a distinguished part in the animal and vegetable kingdoms; for, without its presence, no organized body could exist: when it is withdrawn, the once living form becomes rigid and dead.

Its effects are not less important when produced in inanimate matter, for it is heat which brings about *changes* in the *volume* and in the *aggregate form* of bodies; by it also many substances are rendered luminous; by it their electrical and magnetic condition is influenced; and, lastly, by it the chemical action of bodies on one another is greatly affected.

In consequence of the influence which heat exerts on all organic life, man himself may be regarded as, to a certain degree its slave; viewed from another point, he is the master of this powerful agent, controlling and directing its operations on other bodies at his bidding. The use made by man of this power, in supplying his natural and artificial wants, is so varied and important, that if deprived of these resources, he would become as helpless as the beasts of the field. These considerations may well incite a desire to become better acquainted with the nature of this important agent, and with its mode of operation.

§ 360.

Heat, like gravity, is a universal force; it moves according to its own peculiar laws, and when certain conditions are fulfilled, it is in a state of equilibrium. Heat is said to be *free*, or *sensible*, when it displays a tendency to establish equilibrium, by equally diffusing itself in all surrounding bodies; hence it is in incessant motion, passing from one to another. The quantity of it present at any moment in a particular body is said to be the *temperature* of that body. When its movement ceases, and it is in a temporary state of repose, intimately uniting itself with the atoms of matter, and not causing any change of aggregation, nor apparently tending to do so, we then say that it is *latent*.

§ 361.

By the term *heat* we sometimes mean both the cause and the effect; the former, however, is more accurately expressed by the word *caloric*, heat serving to mark the science which treats of the properties, effects, and laws of caloric.

Heat expresses an increase, as *cold* does a diminution in the sensation of warmth; heat and cold are therefore positive and negative magnitudes, resembling in this respect light and darkness. Both sensations are merely relative, the feeling of heat arising when more caloric is received by our bodies than is required in a normal state of vitality. The feeling of cold is excited when a portion of the requisite warmth is abstracted. Probably, these opposite sensations are merely the results of a change in the volume of our organs; that is to say, *heat* is the *sensation* caused by the *expansion*, and *cold* the *sensation* caused by the *contraction* of the parts of our bodies.

§ 362.

We are as imperfectly informed as to the nature of heat, as we are with regard to the nature of light. We know that it exists only by its effects: but to explain these, we are obliged to have recourse to theory. The principal hypotheses will be briefly noticed here; but at the conclusion of this section, they will be treated of at greater length.

According to the more ancient theory, it was regarded as an imponderable material substance, which, being combined with bodies, under various modifications, produced all the phenomena of heat. Other philosophers considered heat to be merely modified light, assuming that an identity subsisted between the two. The opinion most generally received, in modern times, is that the phenomena of heat, like those of light, are best explained, by attributing them to the undulations of an æther, whose existence we assume, the velocity with which the fluid moves being less when it produces heat than when it generates light.

II. CHANGE IN THE VOLUME OF BODIES CAUSED BY HEAT.

§ 363.

Experience teaches us that *heat increases the volume* of a body. When the sensible caloric in a body is increased, or its temperature is raised, then the body dilates; but when the temperature is lowered, its volume is diminished. Both these effects admit of being measured; the dilatation and contraction are equal in all directions, a small number of crystals only excepted.

This effect of heat has been explained on the supposition that the increase of caloric between the atoms of any body causes them to recede, and that the decrease of the caloric allows them to approach other. According to La Place, heat is itself the repulsive force that, residing in the atoms of which a body consists, drives them asunder when it becomes increased; and when this force is diminished, the power of attraction draws them together. According to Ampère's theory, the changes in a body's volume are owing to the different intensity of the oscillations performed by the æther, which he supposes to exist between the atoms composing it.

First Expt. Change in the volume of solids. — An iron or brass ball, which just goes through a ring, will lie upon it, if heat be applied to it. If left in this position, the ball will, on cooling, fall through the ring. In firing red-hot shot the expansion of the metal has to be considered.

Second Expt. Change in the volume of fluids. — Fill a glass tube partially with quicksilver, alcohol, or water; apply heat, and the liquid will gradually fill the whole, or the larger part of the tube. To show this still better; let the closed end of the tube be enlarged into the form of a globe. On the cooling of the fluid it gradually contracts, and descends the tube.

Third Expt. Change in the volume of gaseous bodies. — A bladder partly filled with air, becomes quite tense if held near a good fire . allow the air to become cool again and the bladder will once more be flaccid, as at first.

Procure a glass tube, about 2 feet in length, having a bulb at one end, the bore being about a line in diameter; introduce a drop of some coloured liquid in such a manner, that it shall stand nearly in the middle of the tube, and thus part the air in the bulb and the one end of the tube from the external air which fills the other end. Heat the bulb, and the air within will dilate, and drive forward the drop of liquid along the tube. Plunge the bulb into cold water, and the air will instantly contract, as the little drop of liquid, which acts as an index, will show.

If a bulb, or retort, such as we have just described, be fitted up with a tube bent downwards, we can cut off all communication between the external air and that within the bulb by immersing the extremity of the tube in a vessel of water. Heat the bulb by placing a spirit-lamp beneath it, and the expansion of the air will be made apparent by the ascent of small bubbles through the water. Remove the lamp, and the air on cooling will resume its original dimensions; the pressure of the atmosphere will force into the bulb a quantity of water equal in volume to the air which escaped. — By adopting such an arrangement as the above, vessels with narrow apertures may be filled with little difficulty.

The exceptions to this law in the contraction of damp clay or wood on the application of heat are apparent only and not real, for these substances contain a large quantity of water which is converted into steam, and is disengaged from the solid body; baked clay and thoroughly dry wood will be found to dilate when their temperature is raised in the same manner as other bodies. — Many molten liquids at the very point when they begin to solidify expand more or less: iron, bismuth, sulphur and water are remarkable instances of this peculiarity, which seems to result from the bodies assuming a crystalline structure. (§ 88.)

A. *Thermometry, and the Instruments for Measuring Free Caloric.*

§ 364.

Our sense of feeling enables us to judge relatively as to the temperature of any body, but it cannot inform us of the quantity of sensible heat the body may contain. We however possess the means of estimating this if we observe the change in volume consequent on the application of different degrees of heat to bodies. Substances to be available for this purpose must possess, either absolutely or within certain limits, the property of varying in bulk proportionally to the quantity of heat which acts upon them.

Instruments contrived to measure the free caloric at no very high temperatures are called *thermometers;* such as are made to show high degrees of heat are termed *pyrometers;* and in both cases the bodies whose change of volume serves as an index are called *thermoscopic substances.* The liquids generally employed are mercury and spirit-of-wine; but for many purposes we use, instead of these, the atmospheric air and metals. The thermometer derives its name from the thermoscopic substance employed; thus, a mercurial thermometer, a spirit-of-wine thermometer, &c.

§ 365.

The principal matter in these instruments is the choice of the thermoscopic substance, the determining of two fixed normal points, by which the length of the scale will be regulated, and the system of graduation to be adopted.

The thermometers in most general use are the *mercurial* and the *spirit of-wine thermometers:* they consist of a cylindrical capillary glass tube, whose bore must be equal throughout its entire length: a bulb is blown at one end of the tube; this bulb and a small part of the tube are filled with quicksilver or with coloured spirit-of-wine, and the open end of the tube is hermetically sealed.

Use of the bulb. — It is important that the bore should be equal throughout, that the mercury be pure, and the vacuum in the tube perfect.

§ 366.

Since we are not acquainted with the limits within which the agency of heat is confined, *i. e.* we do not know either the maximum temperature or the temperature of the absolute zero, we are obliged to select two normal points by which to determine the extent of our scale. These temperatures must be constant in the bodies by which they are measured; they must also be stable for some length of time; and, lastly, they must be such as can be readily found at any time and in any place. The temperature of melting snow or ice determines the position of one of these fixed points and that of pure boiling water gives the other. The former of these is called the *freezing point* and the latter the *boiling point*. The space between is the *fundamental distance*, or length of the scale. The length of the degrees will depend on the system of graduation adopted: the degrees are marked sometimes on the tube itself, but where extreme accuracy is not required, they are cut on a plate of glass, metal, ivory, or wood, to which the tube is fastened.

> To find the freezing point, the thermometer is placed horizontally in a vessel of pure melting snow or ice: the thermoscopic fluid in the tube contracts, until after a short time it takes up a settled position, to which it will invariably return as often as the tube is taken out of the melting ice and again put into it, wherever and whenever it may be done; a proof this that the temperature of melting snow and ice is constant. — It has been noticed that if the freezing point be marked soon after it has been thus found, on plunging the instrument after the lapse of several months into melting ice the fluid will become stationary in the tube from ½ a degree to 2 degrees above the original freezing point. It is supposed that this is owing to a contraction of the bulb, which is gradually brought about by the continued pressure of the atmosphere. — To secure a thermometer from this source of inaccuracy, it is sufficient to postpone for twelve months the marking of the freezing point, by which time the adjustment of the bulb will be completed. — The boiling point is found by laying the thermometer in distilled boiling water, when the fluid will dilate until it reaches a certain expansion, where it becomes stationary. Now, as the temperature of heated water decreases with the depth below the surface, and as the whole thermometer ought to be exposed to an equal degree of heat, it follows that the boiling point will be most accurately determined by placing the instrument horizontally in the

steam just above the surface of the water. Again; the temperature at which water boils varies according to the pressure of the atmosphere, or altitude of the barometer, a fact of which we shall speak more at length presently, and of which an experimental proof has been given already in § 196., where the first experiment was to boil lukewarm water under an exhausted receiver. Hence it is evident why we must always have regard to the height of the barometer in determining the boiling point: consequently, it is found either when the barometer is at a mean altitude (in Germany 28 Paris inches; in France 0·76m.; in England 30, or more exactly 29·8, English inches, § 193.); or else a correction is made if the barometer stands at any other height. Egen found from careful experiment, that the correction for every tenth of an inch which the barometer is above or below this mean height is $\frac{1}{1000}$th part of the interval between the boiling and freezing points. When, therefore, the altitude of the barometer exceeds 29·8 English inches, we must add this quantity to the standard; and when the altitude is less than 29·8 inches, we must deduct it.

Any person may easily satisfy himself of the stability of these normal temperatures by immersing a good thermometer in melting snow and boiling water.

Lastly; when rigid accuracy is required, we must note the influence which a change of temperature exerts on the length of the scale itself; for this reason glass scales are superior to all others, that substance being but slightly affected by variations in temperature.

§ 367.

No one scale has yet been universally adopted; those most generally used are the centigrade, Réaumur's, and Fahrenheit's. In the first, invented by Celsius, the space between the freezing and boiling points is divided into 100°; in the second, adopted by Réaumur and De Luc, the same interval is marked off into 80°, the numeration beginning in each of these thermometers at the freezing point, which is marked 0°; in Fahrenheit's, the zero is placed 32° below the freezing point, and the boiling point at 212°, the space between these normal temperatures being divided into 180°.

In the centigrade and octogesimal scales the degrees above zero are called *degrees of heat*, and those below that point are termed *degrees of cold*; but as the position of the zero point is altogether arbitrary, it is more consistent to distinguish them merely by the signs + and −.

From what has been just stated it is plain, that we must not only mention the degree but also the scale by which we measure the temperature of any body. The degrees of one scale may very easily be converted into those of either of the others, their proportions being most simply expressed by the following numbers: —

$$\begin{aligned} R : C : F &= 80 : 100 : 180 + 32 \\ &= 4 : 5 : 9 + 32 \end{aligned}$$

or

$$\begin{aligned} R &= \tfrac{4}{5}C = \tfrac{4}{9}(F - 32) \\ C &= \tfrac{5}{4}R = \tfrac{5}{9}(F - 32) \\ F &= \tfrac{9}{4}R + 32 = \tfrac{9}{5}C + 32. \end{aligned}$$

Mercurial thermometers possess the following advantages over those in which any other thermoscopic fluid is used: they are capable of measuring much higher and lower temperatures, since they are available within the limits at which mercury freezes and boils, that is, from —40° to 600° Fahr. Towards either limit of the scale the results are by no means satisfactory, on account of the irregular. contraction and expansion of the metal at very high or very low temperatures. They are also more susceptible of slight variations in temperature than thermometers filled with other fluids; that is to say, quicksilver is more readily affected by any change, and its delicacy is not impaired by length of time. Their great superiority is this, that, within the range of ordinary temperatures, *i.e.* between 13° and 212° Fahr., the expansion and contraction of the mercury is exactly proportional to the increments and decrements of the heat.

Spirit-of-wine thermometers are indispensable if we desire to estimate extreme degrees of cold at or near which quicksilver would freeze. These instruments are not available at a heat exceeding 167° Fahr., as the spirit would begin to boil above that temperature. Besides, spirit dilates at a rate not proportional to the increase of heat, but expands more and more with each successive rise in the temperature; consequently, equal degrees on the scale will not represent equal increments in the temperature, as they do in the mercurial thermometer; the correct adjustment of a scale with gradually increasing degrees is a matter of some difficulty.

The first spirit-of-wine thermometers were made by the members of the academy of Florence, towards the middle of the 17th century. The great defect of these instruments was, that they had no fixed point; the temperature of a deep pit was assumed as their zero, and they were graduated at pleasure above and below this arbitrary point. Renaldini first adopted the fixed points of boiling and freezing water, dividing the intermediate space into an arbitrary number of degrees. Réaumur retained the use of spirit-of-wine, and finding that its expansion between these two points equalled 0·08 of its volume, he divided the scale into eighty equal parts, on the supposition that the expansion of the spirit would be proportional to the increase of the temperature. De Luc discovered and corrected this error, and substituted mercury for the spirit-of-wine, though he still retained his predecessor's system of graduation: notwithstanding this important alteration, the thermometer still retained the name of Réaumur. The Swedish philosopher Celsius divided the scale into 100 equal parts. His system of graduation is commonly adopted in Sweden and France, and in Germany it is rapidly supplanting Réaumur's. — Throughout England, Holland, and North America, the Danish philosopher Fahrenheit's scale is in use.

§ 368.

Thermometers furnished with an apparatus for marking the highest and lowest points within which they have ranged during a certain time, and which show the temperature to which they have been elevated or depressed even after they have for a considerable time been exposed to a different one, are called *self-registering thermometers*. The best known are Six's and Rutherford's. They both show the maximum and minimum temperatures by means of a small index, which is easily moved up and down by the mercury and spirit, and which is made to remain behind when the fluids recede on having attained their highest elevation and their greatest depression.

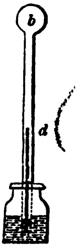
§ 369.

The atmospheric air is employed as the thermoscopic fluid in the *air thermometer*. It possesses this important property, that it retains its form of aggregation under the most extreme degrees of heat and cold that have yet been observed. Its change of volume, too, is very nearly proportional to the increase and decrease of the heat. For these reasons it is the very best thermoscopic substance that can be used. As, however, the changes in the volume of air are not visible to the eye, as those of mercury and spirit-of-wine are, we are obliged to enclose a column of air in the thermometer tube by means of a second column of quicksilver, spirit-of-wine, or some other fluid, in order that the dilatation and contraction of the air may be rendered perceptible by the movements of the other fluid. Now, as such a column of air will expand and contract, not merely in obedience to the action of heat, but will be also affected by the variations in the atmospheric pressure, it is clear that its indications will be the result of a complex force. Besides allowing for the variable altitude of the barometer, we must note the pressure of the column of mercury, or other fluid that may be used. For these reasons the air thermometer is ill-suited for ordinary purposes, though for scientific uses it is valuable on account of its extreme delicacy, as also because the variations in temperature are imparted so readily to the air; and, lastly, because the variations in the volume of aeriform bodies exceed those which obtain in solids and liquids. By virtue of the first of these properties, air is the only accurate measurer of the exact degree of heat at every possible temperature.

The air thermometer is the oldest instrument that has been invented to measure the changes of temperature. It was first made about the middle of the 17th century, by a Dutch countryman, named Cornelius Drebbel; or, as others say, by the physician Sanctorius.

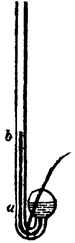
Drebbel's air thermometer (*fig.* 102.) consisted of a common glass tube, at the end of which a bulb *b* was blown; the open end of the tube was immersed in some coloured fluid which mounted part of the way up, as to *d*. If the temperature rose, the portion of air enclosed between *b* and *d* expanded, and forced downwards the fluid below the level *d*; conversely, if the temperature were lowered, the air would contract, and the ascent of the fluid above *d* would follow. This instrument was extremely incomplete, having no fixed point, the graduation of it being altogether arbitrary, and the elevation of the fluid being in part dependent on the pressure of the atmosphere.

Fig. 102.



Amonton's air thermometer, which was an improvement on the original form, made about the commencement of the 18th century, consisted of a tube, like a common barometer tube (*fig.* 103.), but having a close bulb and an open end. This bulb was half filled with mercury, and so was a portion of the tube. The heat was therefore measured by the expansive force of that portion of air which was contained in the bulb. The expansive force itself was to be estimated by the difference between the levels *a* and *b*, and by the altitude of the barometer at the time of observation. To obtain results approximating to the truth, we must farther take into consideration the expansion of the mercury.

Fig. 103.



We have already remarked, that the variations in the volume of air are very nearly proportional to the increase or decrease in the quantity of heat. For this reason air thermometers are particularly useful in comparing the rate at which other thermoscopic substances dilate. They are used principally to correct mercurial thermometers and show their deviations when checked, by comparing their results with those given by such a normal thermometer. Dulong and Petit carefully compared the mercurial and air thermometers, and constructed tables of their differences, from which it would appear, that from −20° to −34° Fahr., the deviation of the mercurial thermometer from the air thermometer does not amount to more than ¼th of a degree at a maximum, that from −13° to 212° the two thermometers agree, from which point the deviation, at first very small, increases with the temperature till it amounts to 18°, at the point where mercury boils.

The following formulæ will enable us to reduce the degrees of a mercurial thermometer for temperatures above the boiling point, to the actual degree or degrees as shown by an air thermometer. Let t' be the degrees, as shown by the mercurial thermometer, and t those shown by the air thermometer; then, for the centigrade scale,

$$t = t' - \tfrac{1}{4}\,[0{\cdot}09\,(t'-100) + 0{\cdot}00028\,(t'-100)^2];$$

for Réaumur's,

$$t = t' - \tfrac{1}{4}\,[0{\cdot}09\,(t'-80) + 0{\cdot}00035\,(t'-80)^2];$$

and for Fahrenheit's,

let $t'' = t' - 32$,

$$t - 32 = t'' - \tfrac{1}{4}\,[0{\cdot}09\,(t''-180) + 0{\cdot}000156\,(t''-180)^2].$$

§ 370.

The *differential thermometer* is an air thermometer of peculiar construction. It consists of two portions of air enclosed in two glass balls, connected by a common glass tube with a fine bore; a column of some fluid (either coloured spirit-of-wine, or sulphuric acid) is introduced, so as to keep these portions of air distinct. If heat be applied to one ball, the air in it expands, and forces the fluid along the tube towards the other ball; if its temperature be lowered, the converse happens.

This thermometer can, it is plain, show only the difference in the expansion or contraction of the air enclosed in one of these bulbs, and hence its name. If both bulbs be exposed to equal degrees of heat or cold, as happens when the instrument is placed freely in atmospheric air, no motion will be observable in the column of fluid.

On account of its extreme delicacy, this thermometer is very serviceable in indicating small local differences in temperature. Rumford's and Leslie's are the two forms of this instrument most generally known.

Rumford's *differential thermometer* is represented in *fig.* 104. *a a* are the two glass bulbs, containing each a portion of atmospheric air, separated by a small quantity of coloured spirit or sulphuric acid at 0, from which point the scale is graduated right and left, either arbitrarily, or according to one or other of the three systems in general use.

Fig. 104.

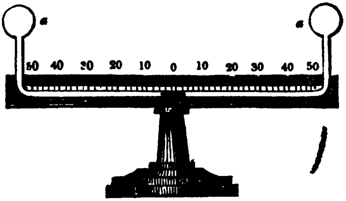
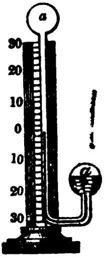


Fig. 105. shows the construction of *Leslie's differential thermometer.* *a a*, as before, are the two bulbs containing atmospheric air; but the lower one is partly filled with coloured fluid, which also rises in the glass tube to the zero point 0. The degrees run both ways, up and down, as in Rumford's thermometer.

Fig. 105.



Professor Schmidt has constructed a similar apparatus, but much more sensitive than either of those already noticed; he states that it is capable of measuring differences in temperature of $\frac{1}{3000}$ of a degree of Réaumur's scale, equal to $\frac{1}{6750}$ of a degree of Fahrenheit's.

(For a further description of this instrument, the reader is referred to Gehler's Phys. Wörterbuch, ii. 535., ix. 994.; or to Schmidt's Handb. d. Naturl. 1826, p. 395.)

§ 371.

Solid bodies also, especially metals, are sometimes used as thermoscopic substances, but these thermometers have not been so generally adopted as others in which a fluid is employed. A strip of metal in these instruments, by its contraction and dilatation, is made to set in motion a lever of unequal arms, the longer arm acting as an index to point to the degrees on the scale. The thermometers made on this principle by Breguet of Paris and Holzmann of Vienna have externally the shape of watches.

§ 372.

Instruments, called *pyrometers*, are used to measure high degrees of temperature, such as those in furnaces and smelting-houses, as thermometers of the ordinary construction would be destroyed if subjected to the action of such intense heat. The best known and most generally used is *Wedgwood's*: it measures the degrees of heat in the fire or furnace to which it is exposed by the contraction of a cylindrical piece of fine porcelain clay, whose dimensions are measured by observing how far it will descend between two plates of metal placed close together, and inclined at an angle of 0·5″ at one end, and at an angle of 0·3″ at the other. The cylinder should be of such a size as just to pass the wider aperture of the planes where the graduation begins when of a deep red heat. On exposure to a higher temperature, the clay will contract still more; and on being placed between the converging plates it will show, according to Wedgwood's scale, the degree of heat to which it has been subjected. Wedgwood placed the zero point of his scale at 1077·5° Fahr., and estimated each degree of it to be equivalent to 130° of Fahrenheit's. Guyton Morveau called in question the accuracy of this estimate, and from his investigations supposed 0° of Wedgwood's scale to correspond with 512° Fahr. nearly, and each degree he made to be equal to only a little more than 60° Fahr. The objections to this pyrometer are, that the clay is not always exactly the same in its composition, and that, if subjected for a longer time to a lower heat, an equal contraction ensues to that which would have happened had it been exposed for a short time to a high temperature.

Pyrometers of more modern construction act chiefly in consequence of the expansion of platina, a metal capable of resisting the greatest heat of any furnace to which it has yet been exposed without melting. Petersen's is remarkable for its extreme delicacy. This instrument measures differences in temperature ranging from + 20° to + 2000° of the centigrade scale, equal to from 68° to 3632° of Fahrenheit's; and the scale furnished with a nonius shows the variations for every 2° C.; its susceptibility is such, that it shows the difference between the temperature of two rooms in from two to five minutes of time.

It is worthy of remark, that no pyrometer yet constructed fully satisfies every requirement, as there exists a discrepancy in their results; besides that, we are not sure, with regard to all of them, that their measurements are really proportional to the quantity of sensible caloric.

When bodies are raised to very high temperatures, we distinguish them by the intensity of the light which the heated substance gives out: thus, a *dull red heat* (1480° F.), *bright red heat* (1830°), and *white heat* (2370°—2910°).

B. *Difference in the Change of Volume of Substances, according to their Form of Aggregation.*

§ 373.

An equal increase or decrease of heat does not cause an equal change of volume in all bodies. It has been found experimentally, that the action of heat excites the smallest alteration in solids, a greater in liquids, and in gaseous bodies an alteration greater than in either of the other classes of substances. Hence it follows, generally speaking, that the change in volume induced by heat will be greater or less according to the greater or less density of any body. Viewed thus, we may consider heat and cohesion as antagonist forces; the one representing the repulsive, and the other the attractive force in a body.

§ 374.

The cohesive force of solid bodies diminishes with their expansion by heat; and the more powerful the operation of the latter agent, the greater the diminution in the cohesive force. As solids exhibit the strongest cohesion, they oppose the chief resistance to dilatation by heat; and, as we should naturally expect, their increase in volume, consequent on an elevation in their temperature, is less than that of bodies under another form of aggregation.

Solids dilate pretty regularly, at temperatures between the freezing and boiling points of water; *i. e.* between 32° and 212° F.; consequently, equal increments of heat correspond with equal increments of volume. At the higher temperatures, the expansion proceeds at a greater rate than the successive additions of heat.

The degree of expansibility varies in different substances. The metals possess this property in the highest degree; but even among them there are great differences; in most, however, the change in volume corresponds pretty nearly with their respective readiness to fuse. Earthy substances, as stones and glass, vary less in bulk; and hard dry bodies of the organic kingdoms, such as dry wood, bones, and the like, still less.

Bodies having a uniform internal structure dilate and contract equally in all directions; many species of crystals, however, form striking exceptions to this general rule.

> Mitscherlich says, that the expansion of all crystals with unequal axes is not equal in every direction; but that they invariably dilate less in the direction of their longer, than in that of their shorter, axis.

It is further to be observed, that the linear dilatation of solid bodies is determined by means of pyrometric experiments, and that the attainment of correct results is attended with considerable difficulty. On account of the minute expansion of these substances, we may assume their superficial expansion as double, and their cubical expansion as triple, their linear.

Table X. contains the linear expansion of the more common solid bodies, when raised from the freezing to the boiling point, the length at the former point being called unity. To find the linear expansion for 1° F. take the $\frac{1}{180}$th part of the value given in the table. If the centigrade, or Réaumur's, scale be adopted, divide the same value by 100, or by 80, respectively. The contraction for every degree below the freezing point is to be reckoned equal to the expansion for every degree above it.

§ 375.

The minute changes in volume which heat causes in metals and other solid bodies are not regarded at the ordinary variations in temperature that happen in every day life; its influence cannot, however, be disregarded in bodies which ought to be of some definite size; as, for instance, standards of length or capacity (1), moulds for cannon and other foundry work, pendulums intended to measure time with great accuracy. (2) The influence of heat on solid bodies has to be considered practically, in many instances, on account of the irresistible force with which they expand and contract; and this force must be noticed especially, when several different substances are combined in one piece of mechanism. (3)

TABLE X.

Of the Longitudinal Expansion of different Solid Bodies caused by raising them from a Temperature of 32° to one of 212° Fahr.

Substances.	Length at 212°, length at 32° being = 1.	Index of the Expansion at 212°.	By whom observed.
Earthenware, brown English	1·00012000	$\frac{1}{8333}$	Destigny.
Fir	1·00035200	$\frac{1}{2841}$	Struve.
Glass, a mean	1·00089694	$\frac{1}{1116}$	Lavoisier and Laplace.
Platinum	1·00098390	$\frac{1}{1018}$	Dulong and Petit.
Steel, soft	1·00107956	$\frac{1}{926}$	Lavoisier.
Cast Iron	1·00110940	$\frac{1}{901}$	Roy.
Bar Iron	1·00115600	$\frac{1}{863}$	Borda and Tralles.
Ditto	1·00126660	$\frac{1}{790}$	Dulong and Petit.
Steel, hardened	1·00136900	$\frac{1}{730}$	Lavoisier.
Gold	1·00146606	$\frac{1}{682}$	———
Bronze	1·00181667	$\frac{1}{550}$	Smeaton.
Copper, hammered	1·00184110	$\frac{1}{543}$	Dulong and Petit.
Brass, cast	1·00186671	$\frac{1}{535}$	Lavoisier.
Brass Wire	1·00187821	$\frac{1}{532}$	———
Silver	1·00190974	$\frac{1}{524}$	———
Tin	1·00217298	$\frac{1}{460}$	———
Lead	1·00284836	$\frac{1}{351}$	———
Zinc, cast	1·00294167	$\frac{1}{340}$	Smeaton.
Zinc, hammered	1·00310833	$\frac{1}{322}$	———

A standard measure gives the required length correctly, only at one particular temperature. If the temperature exceed this normal temperature the dimensions of the rod will be too great; if it be less, then the dimensions will be too small; and this variation depends, not merely on the degree of heat to which the standard is subjected, but also to the material of which it is made. Standards of wood or glass vary but little at ordinary temperatures; hence the utility of employing thermometer scales of one or other of these substances in preference to those made of metal. In a metal scale one foot in length, corrections for temperature are indispensable to secure accurate results. Let l be the length at temperature t, and λ the correct length of the standard at the normal temperature τ; and let $1+m$ be the coefficient of the expansion of its material at the boiling point of water; then, from the formula

$$l = \left[1 + \frac{m(t-\tau)}{100}\right],$$

we shall obtain the true length, λ, for the centigrade scale, with sufficient exactness,

$$\lambda = l\left[1 - \frac{m(t-\tau)}{100}\right];$$

and for Fahrenheit's scale

$$\lambda = l\left[1 - \frac{m(t-\tau)}{180}\right].$$

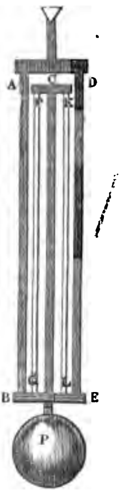
Hence we see why, in accurate barometric measurements, we are obliged to make a correction for the scale of the barometer, according to the temperature at the time of making the observation.

So, also, it is easily perceived why the moulds for all sorts of cast-iron work should be rather larger than the article itself is wished to be.

2.) If a pendulum is intended to serve as an exact measurer of time, we must contrive that its length shall be altered as little as possible through variations in temperature. (§ 103. 1.) Consequently, it is advisable to select for the rod of the pendulum some substance that is but slightly affected by heat, and to place the instrument in such a situation, that it may be subjected to as little change as possible; deal, well seasoned and then soaked in oil and baked, will be found a very good material. The best pendulums, called *compensation pendulums*, are made of different substances, so combined that the effects of heat counteract each other, and the length of the rod remains unaltered.

The commonest compensation pendulum is *Harrison's gridiron pendulum*. It is represented in its most simple form, *fig.* 106. The proper rod C P is of iron; so, also,

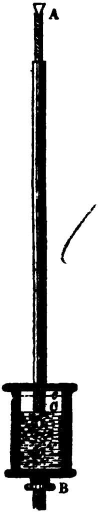
Fig. 106.



are the bars A B and D E; but the inner ones, F G and K L, are of zinc. Now, as both these metals will be affected simultaneously by a change of temperature, so that when the iron expands P is made to descend; but a corresponding expansion of the zinc elevates it; it follows that P, being acted on by two equal antagonist forces, neither rises nor falls. Since the expansion of zinc exceeds that of iron, the bars must not be equal; but such a relation must be established between them, that the elevation or depression of the bob by the one metal may be exactly counteracted by the depression or elevation of the other, with every rise or fall of temperature. This is accomplished by making the lengths of the two metals inversely as their expansions. The lengths of these rods may be determined by the formula, $l = L\frac{i}{z-i}$, l being the length of the zinc bar, L that of the iron, i the expansion of the iron, and z that of the zinc. Now, as the expansion of iron is to that of zinc (Table X.), as $\frac{1}{790}$: $\frac{1}{340}$, or as 1 : 2·324; for these two metals the formula becomes

$$l = L\frac{1}{2{\cdot}324-1} = 0{\cdot}755\,L.$$

One of the most simple, and at the same time ingenious, contrivances, was that of *Graham* (1721), who constructed the *mercurial compensation pendulum.* This instrument consists of an iron rod A B (*fig.* 107.), to the lower extremity of which a branch is fitted to embrace a cylindric glass vessel B C, containing quicksilver. The theory of this pendulum is extremely simple. As the point O of the pendulum's oscillation is about the middle of the vessel of mercury BC, it is clear that an increase in the temperature will lengthen the rod A B, about O *o*, so as to depress the centre of oscillation to *o*; but the simultaneous expansion of the mercury elevates this point to O. This result is exactly attained when the expansion of the mercurial column C B is just double that of the rod A B, *i. e.* when the space C *c*, through which the quicksilver rises in the vessel, is equal to twice O *o*. Now, suppose the distance of the ig. 107.



point of suspension from the centre of oscillation, or the length of the second's pendulum to be 39·13929 inches = 479·67 lines, then A O = 479·67 lines. B O is half the height of the quicksilver in the vessel, and A B the entire length of the metal rod. Now, let i denote the expansion of the iron, and q that of the quicksilver, then A B would expand A B . i, and O B would expand O B . q. In order that these two expansions should counteract each other, it would be necessary that A B . i = O B . q. But A B = 39·139 + O B, whence the equation becomes

$$i\,(39{\cdot}139 + \mathrm{OB}) = q\,.\,\mathrm{OB}\,;$$

$$\therefore\ \mathrm{OB} = \frac{i\,.\,39{\cdot}139}{q - i}.$$

The expansion of iron between the freezing and the boiling points of water, according to Dulong and Petit (see Table X.), is 0·00126, and the expansion of mercury between the same temperatures, according to the same philosophers, is 0·01801, but as Horner says, 0·0175 if the expansion of the glass also be taken into account, thus,

$$i : q = 126 : 1750,$$

or nearly $= 1 : 14.$

and $\mathrm{OB} = \dfrac{39{\cdot}139}{14 - 1} = 3{\cdot}01$ inches.

The entire length of the mercurial cylinder B C will, therefore, be 6·02 inches.

Both the mercurial and the gridiron pendulums will require regulating, the former is corrected by pouring in or taking out of the cup very small portions of mercury, the latter, by turning a screw up or down, so as to raise or depress the point of oscillation.

The compensation in a chronometer depends on the same principle, different metals being so combined as to render the oscillations isochronous.

3.) In tubes for conveying water, steam, or gas, it is necessary to make provision for the expansion and contraction of the metal. Similar adjustments have to be made in machinery into which large pieces of iron-work enter. Room is left to allow for the change of volume in boilers and similar vessels.

To the unequal expansion and contraction of bodies, or parts of bodies, consisting of different substances, or of one substance unequally heated, we must attribute the cracking of glass, of the backs of stoves, of cannon, &c.; also the cracking of metal roofs and of ice with intense cold, and of iron fastenings and girders, which have been fixed when the temperature was very low, and which are greatly expanded and made to fly by the rise in the temperature. Hence, if iron bars be fixed in windows, walls, or other places, room should be allowed at one end for them to play. Generally speaking, this rupture takes place more or less readily, according to the greater or less degree of brittleness which the body possesses: the greater the change of temperature, and the more suddenly it is produced, the more likely a body is to fly, especially if it be of such a nature that the change of temperature is but slowly communicated throughout its mass. Hence we see why thin glasses are less likely to fly when suddenly heated or cooled, than thick ones. The property which glass possesses of splitting in the direction in which it is suddenly heated and cooled, is of great use in a technical point of view, and particularly so, in practical chemistry.

The force with which heated bodies expand is capable of overcoming a prodigious resistance; it sets at defiance the utmost degree of pressure. The same may be said of their power of contraction when cooled. Molard applied this force to restoring the walls of an edifice in Paris to their perpendicular position. From what has been said, the reason becomes apparent for putting on the tires of wheels, and all rings intended to secure wood-work in its place when heated.

§ 376.

We have already said, that the dilatation of fluids by heat exceeds that of solids (§ 372.); the degree of their expansion varies in different fluids. Almost all bodies of this class which have yet been investigated, do not vary in volume proportionally to the increase or decrease of their temperature; but, on the contrary, a progressive increase in their expansion seems to accompany a rise in temperature. To this general rule mercury offers a remarkable exception, as the variations in its volume are exactly proportional to the variations in its temperature between $-13°$ and $+212°$ Fahr.

The principal fluids, whose dilatations have been accurately determined, are water, mercury, and alcohol.

The dilatation of water from 32° to 212° = 0·04292798 = $\frac{1}{23}$, of mercury = 0·01801802 = $\frac{1}{55}$, of pure alcohol = 0·12548 = $\frac{1}{8}$ of its volume.

The expansion and contraction of water has been repeatedly investigated. This fluid has the remarkable property of not acquiring its maximum density at the freezing point; that is to say, at the point where it becomes converted into a solid; but, on the contrary, this change of its form of aggregation is accompanied with an extraordinary expansive force. Experiments were performed at Warsaw, in the winters of 1828 and 29, to determine the force with which freezing water expands. For this purpose cast-iron shells were filled with water, the hole was closed with an iron screw, and the shell exposed to the cold: one of these shells burst into two unequal portions, of which the smaller was projected to a distance of 10, and the larger to a distance of 7 feet from their original position; another shell burst into two pieces, one of which was cast 4 feet. The expansive force of freezing water brings about important changes in the surface of our earth, especially in mountainous districts, such as Switzerland. Formerly it was believed that water acquired its maximum density at 4·1° Cen. = 39·38° Fahr.; but the more recent and exact experiments of Munke and Stampfer have fixed this point at 38·8°, or 38·75° Fahr. — Importance of this peculiarity, on account of the formation of ice in the sea and in rivers. — In order to determine accurately the specific gravity of any substance, it is indispensable that we should know the temperature of the water in which it is weighed. (See above, § 173 and 176.)

The changes in the volume of mercury are important to be known, principally, because of their influence on the height of the barometer (§ 199.), and, accordingly, they too have been repeatedly investigated. According to Flaugergue's most recent and careful experiments it appears that between −13° and +212° the expansion of this metal is strictly uniform, and that this expansion, according to Dulong and Petit, is for each degree Fahr. $\frac{1}{9990}$ = 0·0001001001, for each degree C. $\frac{1}{5550}$ = 0·00018018, and for each degree R. $\frac{1}{4440}$ = 0·000225225. In consequence of the regularity of its expansion, mercury is the fluid most commonly used in thermometers. (Comp. § 366.)

The expansion of alcohol has also been investigated repeatedly, because of the use made of this fluid as a thermoscopic substance, for observations at a low temperature. Munke's experiments are the most recent, and the results he has obtained the most satisfactory. He makes the expansion of pure alcohol (0·806 at 32° Fahr.) to be $\frac{1}{1800}$ for every degree of heat above this temperature, the volume at 32° being reckoned 1; the expansion, however, at 43° is rather more than $\frac{43}{1800}$, being $\frac{44\frac{8}{10}}{1800}$. Alcohol contracts with the like regularity for every degree below the freezing point of water.

Munke has further established the fact, that pure alcohol has the greater expansive and contractile force, and that this force diminishes in proportion to the quantity of water combined with it. He states the volume of pure alcohol at 122° Fahr. to be = 1·056071; that of water at the same temperature to be = 1·011570; and that of alcohol, not perfectly pure (*i.e.* whose specific gravity, at 54½° Fahr. is 0·808) to be = 1·054394.

§ 377.

As all aëriform bodies have, naturally, a tendency to expand or increase in volume (§ 179.), the expansive force of heat in them meets with no such resistance as is offered to it by both solids and non-elastic fluids through the cohesion of their component particles. Hence we are justified in regarding the effect of heat on aëriform substances, as the most certain measure of the free caloric, inasmuch as it has no cohesive force to overcome.

The atmospheric air and all gases dilate almost equally and very nearly in proportion to the increase of temperature. The absolute magnitude of this expansion greatly exceeds that of either solids or liquids, amounting to 0·3665, or $\frac{11}{30}$ of its volume, when raised from 32° to 212°, so that the expansion for every degree above freezing point is 0·002037, or $\frac{11}{5400}$; or for every degree of the centigrade scale 0·00366 or $\frac{11}{3000}$.

The experiments of Gay Lussac, Dulong, and Petit had led philosophers to believe that the expansions of all gases at equal changes in temperature were exactly equal and proportional to the increase in the heat. The co-efficient of their expansion from 32° to 212° was supposed to be 0·375, or $\frac{3}{8}$ of this volume. Rudberg was the first who threw out a doubt as to the correctness of this value, and the experiments lately published by Magnus and Regnault have confirmed the justness of his suspicion, so that 0·3665 may now be considered as the true co-efficient for the expansion of atmospheric air, this result having been arrived at by the two philosophers last named, by methods perfectly independent of each other.

Magnus and Regnault further found that this co-efficient was not common to other gases; the following are the values they determined by investigation, for the gases given below: —

	Regnault.	Magnus.
For Hydrogen	0·36613	0 365659
Nitrogen	0·36682	
Carbonic oxide gas	0·36688	
Carbonic acid ditto	0·37099	0·369087
Nitrous oxide ditto	0·37195	
Cyanogen ditto	0·38767	
Sulphuric acid ditto	0·39028	0·385618

Regnault discovered, also, that this co-efficient for their expansion is variable; that it increases when the density of the gas increases, but in a less ratio; and that this increase differs in different gases. The following are the values for the gases named below: —

ATMOSPHERIC AIR.

Pressure at 32°. Inches.	Pressure at 212°. Inches.	Density of Gas at 32°. Do. of atmosphere at 32°, and 29·92196 in.=1	Index of Expansion 1+180*a*.
4·31978	5·87848	0·1444	1·36482
29·92196	—	1·0000	1·36587
143·92305	196·54358	4·8100	1·37091
CARBONIC ACID GAS.			
29·86172	40·73087	1·0000	1·36856
141·65961	187·36777	4·7318	1·38598

In the third column the densities of the gases are given at the temperature of freezing water; from which it appears that the variation in

Atmospheric air is from 0·1444 to 4·81, or 1 to 33·3.
Carbonic acid gas - - - - 1 to 4·732.

For this difference, therefore, we must change the index of expansion of

Atm. air from 1·36482 to 1·3709, or 0·0061 nearly
Carb. ac. gas 1·36856 — 1·38598 — 0·0174.

From what has been said above it follows, that the expansion of carbonic acid gas increases with the pressure more rapidly than that of atmospheric air. Regnault found by his experiments on hydrogen, that the expansibility of this gas scarcely varied at all.

Let V = the volume of a gas at 32°, v that of a gas at any number of degrees t°, above or below that point, and e the index of its expansion for 1°; assuming that the atmospheric pressure or height of the barometer remains unaltered, then

$$V : v = 1 : \pm et,$$

$$\therefore \quad v = V(\pm et).$$

That is

$$\text{I.} \begin{cases} \text{for Fahr. } v = V(1 \pm 0{\cdot}002037t). \\ \text{for Cent. } v = V(1 \pm 0{\cdot}00366t). \end{cases}$$

Again let b represent the mean, and b' the observed altitude of the barometer, v the volume of the gas at b, and v' that at b'; then by Mariotte's law (§ 197.),

$$v : v' = b' : b;$$

whence
$$v' = \frac{vb}{b'} = \frac{b}{b'} \,.\, V(1 \pm et),$$

and
$$V = \frac{b'}{b} \cdot \frac{v'}{(1 \pm et)}.$$

Whence

$$\text{II.} \begin{cases} \text{for Fahr. } v' = \dfrac{b}{b'} \,.\, V(1 \pm 0{\cdot}002037t), \\[2ex] \text{for Cent. } v' = \dfrac{b}{b'} \,.\, V(1 \pm 0{\cdot}00366t). \end{cases}$$

$$\text{III.} \begin{cases} \text{for Fahr. } V = \dfrac{b'}{b} \cdot \dfrac{v'}{(1 \pm 0{\cdot}002037t)}, \\[2ex] \text{for Cent. } V = \dfrac{b'}{b} \cdot \dfrac{v'}{(1 \pm 0{\cdot}00366t)}. \end{cases}$$

Formulæ I. are used to calculate how much the volume of a certain quantity of gas increases with a particular rise or fall of its temperature, the pressure to which it is subjected continuing the same. By formulæ II. we determine the relative proportions between a volume of gas at any height whatever of the barometer and thermometer, and an equal volume of the same gas at 32° F. (0° Cent.), and at the normal barometric altitude. Lastly; formulæ III. are used to reduce the volume of a gas at whatever altitudes of the barometer and thermometer it may have been observed, to 32° of heat and to the mean barometric altitude (29·8 inches).

§ 378.

A second important result, owing partly to the properties of gaseous bodies themselves, and partly to their perfect elasticity (obs. § 179.), is this, that if a gas be enclosed within such limits as prevent its expansion, on applying heat to it we shall increase its elastic force in the same proportion as the heat is increased, but no change will follow in the material constitution of the aeriform body.

The increased force of expansion brought about by the heat may be measured by ascertaining the amount of the gas's pressure, as was done in the case of condensed air. (§ 245.)

If the expansive force be so increased by raising the temperature that the gas overcomes the resistance offered by the enclosing body, then the latter will be driven forward by the expansion of the air in that direction in which it gives way.

Expt. Heat the air above the water in a Hero's ball, and a jet will ensue.

For a similar reason when gunpowder is ignited, the expansive force of the gas is greatly increased by the quantity of free caloric generated.

III. PROPAGATION OF HEAT.

§ 379.

The free caloric endeavours to establish an equilibrium as regards heat in all bodies; that is to say, it has a tendency to impart itself to all substances. Our every day's experience confirms the truth of this assertion, as we find all heated bodies give out their free caloric to surrounding objects until they are raised to the same temperature with themselves. The time required to effect this depends on the material of the body to be heated, on its mass and magnitude, and on the nature of its surface.

This motion of free caloric, by which equilibrium is re-established, is of two kinds, viz. *Radiation* and *Conduction*. The main distinction in these two modes is, that heat is said to be propagated by radiation, when it is communicated from one body to another through an intervening space; it is said to be communicated by conduction, when it is transmitted through the interior of any body.

A. *Of Radiant Caloric.*

§ 380.

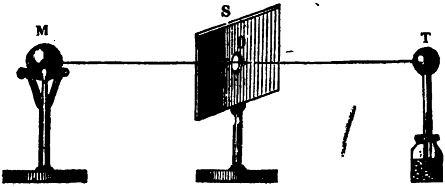
Free caloric when *radiant* possesses its maximum mobility, and in this state it obeys the same laws with light.

All bodies, whatever may be their temperature, radiate heat, which is *propagated from their surfaces in all directions in right lines.* Heat is therefore diffused in a manner similar to that in which light is propagated from self-luminous bodies, and in this respect the *rays of heat* have a close affinity to those of light. (§ 277.)

It has been found that the same law obtains in regard to heat as has been discovered to prevail in all other forces radiating from a centre (*ex. gr.* Gravitation, § 29.; Sound, § 260.; and Light, § 281.), viz. that *the intensity of the radiation diminishes as the square of the distance increases.* Ritchie and Melloni have in modern times experimentally proved the truth of this law.

A person may convince himself in a very simple manner of the radiation of heat by standing with his face towards a heated stove, or any substance in a state of combustion. A sensible warmth will be felt; the more strongly the nearer the observer approaches the source of heat. This effect ceases altogether if a screen be interposed between the face and the fire. — Its intensity may be measured thus,

Fig. 108.



Expt. Place the bulb of a delicate air thermometer T, *fig.* 108., near to a heated metallic body M, and between them interpose a screen S, on which the rays of heat may be received. — With this arrangement the thermometer will not show any rise of temperature; but if the screen be removed, or, what will be still better, if an aperture *o* be uncovered, so that the rays from M can pass in a right line to the bulb T, the fluid will rise instantly, and the intensity of the heat may be measured by placing the thermometer at different distances from the opening in the screen.

§ 381.

Heat is propagated with an extraordinary velocity. It was formerly believed that it travelled as fast as light, but modern scientific research has shown that the rate at which heat is radiated from the sun is only $\frac{4}{5}$ths of the velocity of light, or about 163,600 miles in a second.

Von Wrede measured the velocity with which heat is propagated in a manner as simple as it is ingenious. He inferred that if heat and light in the sun's rays possessed unequal velocities, then their aberrations must also be unequal (§ 286. obs.); and consequently, that the image of the sun formed in a telescope by the calorific and by the luminous rays would not exactly coincide, but would be inclined the one to the other in a direction parallel to the ecliptic. One consequence of this would be, that the temperatures on the eastern and western edges of the image of the sun would not be equal. By means of a thermo-electric calorimeter (an instrument of which a detailed account will be found in the section on thermo-electricity) placed in the telescope, it was found that the temperature of the eastern edge of the sun's image exceeded that of the western edge, and consequently the velocity of the rays of heat was less than that of the luminous rays. The mean of a great number of observations gave the proportion stated above. He noticed, however, that the requisite number of observations could not be considered to have been yet made to authorise the belief that the proportion given is indubitably correct.

§ 382.

A very striking analogy subsists between the radiation of heat and light, inasmuch as different substances are found to have very different capacities for *emitting*, *reflecting*, *absorbing*, and *transmitting* the rays of heat, just as we have already remarked, in the preceding section, to be the case with regard to the rays of light.

§ 383.

The *radiating power* of any body depends on its temperature and on the nature of its surface. In general, the rays emitted by a heated body will be more numerous and more intense the higher its temperature. At equal temperatures metallic surfaces radiate less heat than others, and such as are smooth or polished less than rough surfaces.

Leslie established this fact experimentally in the following manner: —

Expt. He procured a cubical vessel of block tin, one side of which he polished, the second he made rough by scraping, the third he covered with a glass plate, and the fourth he blackened with lamp-black. — He then filled the vessel with boiling water and presented the different sides in succession to a delicate air thermometer, preserving the same distance in each instance, and found that the polished face radiated the least, and that which was covered with lamp-black radiated the most.

Leslie found their radiating powers to be

Lamp-black -	100	Rough Lead - -	45
Water - -	100	Mercury - - -	20
Writing-paper -	98	Polished Lead - -	19
Glass - -	90	Polished Iron - -	15
Tissue-paper -	88	Tin, Silver, Copper, Gold - -	12
Ice - - -	85		

§ 384.

The rays of heat which fall upon any body will be reflected back from its surface, according to the same laws as regulated the reflection of the rays of light. (§ 289.) This *reflecting power* of different substances varies according to the nature of their surface, and the material of which they consist. The most complete reflection is that from metallic surfaces. Leslie says, the greatest reflection is from brass; Nobili and Melloni say from mercury and copper. All non-metallic bodies, whatever the nature of their surfaces, have either very low reflecting powers, or none at all.

Leslie represents the reflecting powers of the substances given below by the following numbers: —

Brass - - -	100	Tin-foil, done over with mercury - - -	10
Silver - - -	90	Glass - - -	10
Tin-foil - - -	85	Glass, smeared with wax or oil - - -	5
Block-tin - - -	80		
Steel - - -	70		
Lead - - -	60		

The following experiments will serve to show that the reflection of the rays of heat obeys the same laws as that of light.

First Expt. In the focus *a* (*fig.* 152. p. 264. Vol. I.) of a metallic concave mirror *m n*, place a red-hot ball, and the rays impinging on the surface of the mirror will be reflected in a direction parallel to the axis. — A sensitive air thermometer placed in front of the mirror will be affected by the reflection of the rays at a considerable distance from the focus; but if placed on either side of the mirror, the spirit will stand almost or quite at the same level.

Second Expt. Referring to the same figure, if now we imagine *o p* to represent a second similar mirror, having a common axis with *m n*, and a thermometer be placed in its focus, we shall find this instrument to indicate a great rise in temperature, even if the mirrors be placed at a distance of 20 feet apart. — The second mirror *o p* reflects the rays projected into it from the other mirror *m n*, and combines them all in its focus *l*, where we have supposed the thermometer to be placed. — The like result will be obtained in the best vacuum that we can get in the exhausted receiver of an air-pump; whence we infer that the radiation of heat takes place in vacuo the same as in the atmosphere.

By means of the arrangement described above, we can ignite tinder, gunpowder, and similar substances, if in one focus we place a piece of burning coal, and in the other focus one of these bodies which we desire to set light to; if the mirrors are pretty good, this effect will follow when their distance is as much as 40 or 50 feet.

Third Expt. For the burning coal or hot iron placed in one of the foci substitute a lump of ice, or a cup containing some freezing mixture (§ 402.), and the thermometer in the other focus will instantly indicate a great fall in the temperature. — In this case more caloric radiates from the thermometer than from the ice, whence the former suffers a diminution in the quantity of its heat.

In all these three experiments it will be observed that the motion of the heat is performed with extreme velocity. Before the first mirror place a screen of glass, wood, metal, or paper, on which the rays reflected by the mirror may be received, and the thermometer will be unaffected; but at the very instant when the screen is removed, the fluid in the tube will be seen to rise or fall, according as the heated ball or the lump of ice is in the opposite focus. These variations in the temperature will be seen most readily in a very sensitive thermo-electric calorimeter.

§ 385.

Every body impinged on by the rays of heat reflects but a portion of such rays; the remainder penetrating into the interior of the body lose their radiant power, and raise the temperature of the body they enter. This process is termed *absorption*. The absorptive power of a body is inversely as its reflective power, and in many substances it is directly as their power of radiation; that is to say, bodies which radiate heat quickly and powerfully, become also more quickly and more intensely heated than others, when exposed to radiant heat. Besides, it has been ascertained, that the temperature of any body is raised most speedily when the rays fall perpendicularly on its surface; and conversely, that the greater the deviation of the angle of incidence from a right angle, the more slow and feeble is the effect produced; in all these points the analogy between heat and light is striking. (Compare § 294.)

If the temperature of any body continue stationary, this equilibrium may be accounted for on the supposition, that the quantity of heat which it diffuses by radiation is equal to that which it receives by radiation from surrounding objects, and which it either wholly or in part absorbs. On this principle Prevost's *theory of exchanges* is built. This equality in the quantity of heat given out and acquired by radiation, can be established only in such bodies as allow no portion whatever of the heat they acquire to pass through them; whence it follows, that the absorptive power of bodies depends also on their capacity for transmitting heat.

Leslie and Ritchie endeavoured experimentally to determine the ratio between the capacities of bodies for radiating and absorbing heat, and they invariably found that the intensity of the radiation corresponded with that of the absorption in similar bodies with equal surfaces. The more recent and very nice experiments of Melloni have since proved, that this law does not hold good for all substances; if minute differences be disregarded, the general truth of the law may be illustrated by the following experiments:—

First Expt. Cover half one side of a pane of glass with tin-foil, and hold this covered side next a powerfully radiating source of heat, such as a burning coal; then place your hand on the other side, and scarcely any warmth will be felt on that part of the glass which is behind the metal, but on the other portion the heat will be very perceptible. Now turn the pane so as to expose the naked side of the glass towards the rays, and the effects will be reversed. A still greater difference is observable, if that part of the glass which is not covered with metal be coated over with soot or lamp-black.

Second Expt. Blacken one side of a Rumford's differential thermometer (§ 370.) with lamp-black, and coat half the other bulb with leaf-gold or silver; the blackened bulb will exhibit a much greater absorbent power than the uncovered half of the other ball. The difference will be made still greater by throwing the rays on that half which is covered with metal. In performing this experiment care should be taken that both the balls are exposed to precisely equal radiations: this will be best accomplished by placing them both in the sun's rays. The bulbs of other thermometers are sometimes blackened to increase their sensitiveness to the action of heat.

If a body emit more heat than it receives from others, its temperature must necessarily sink. The third experiment (§ 384.) proves this. On this principle investigations have been made to ascertain the relation subsisting between the heat radiated* from the surface of our earth into the surrounding space, and that which is imparted to it by other heavenly bodies, as the fixed stars. For this purpose a concave metallic mirror was fixed in such a position, that its reflecting surface was directed towards the sky: it would, therefore, collect in a focus all the rays of heat which it received from this source. A delicate air thermometer was placed in the focus, and it was found that when the sky was clear the temperature of the thermometer fell below that of another standing in the open-air, but that when the sky was cloudy no difference was perceptible between the two instruments. In the former case, therefore, the radiation of heat from the earth must have exceeded the heat imparted to our planet by the other heavenly bodies. This experiment was originated by Wells; and Delaroche is of opinion, that when the sky is overcast the clouds form a kind of screen, which intercepts the rays emitted by the earth and prevents their escape.

The mutual relation which has been explained in this section, and which has been shown to subsist between the radiation, absorption, and reflection of heat, may be expressed by means of mathematical formulæ. Let h represent that quantity of heat, as shown by a thermometer, which the rays of heat impinging on a body impart in a certain unit of time; let $\frac{h}{m}$ be the portion absorbed by the body, and let the remainder $(1 - \frac{1}{m})\,h$ be reflected; then the fractions $\frac{1}{m}$ and

$\frac{m-1}{h}$ will express the capability of its surface for absorbing and reflecting heat. The value of m is variable according to the nature of the body; it depends also on the temperature t of the radiating body; a surface which absorbs $\frac{h}{m}$ would, if similarly situated, and raised also to the temperature t, emit a quantity of heat represented by $\frac{h}{m}$.

§ 386.

Lastly; *diathermanous* bodies are such as allow the rays of heat to pass through them in much the same manner as diaphanous bodies transmit light; those substances which retain all the heat they receive are called *athermanous.*

Gaseous bodies and a vacuum (as we have already learned from experiments 1 to 3. § 384.) are diathermanous. The power of solids and liquids to transmit heat does not correspond with their respective capacity for transmitting light. As far as we yet know, all perfectly opaque substances, such as the metals, are also athermanous; whence it has been inferred, that a body's power to transmit heat must be dependent on its possessing some degree of transparency.

Rock salt is the most diathermanous of all known solids, and alum the least so; bisulphuret of carbon the most, and water the least, diathermanous of liquids.

Delaroche first discovered the transmissive power of common glass, but the most important discoveries in this branch of science have been made by Melloni, who has investigated the power of many solids and liquids to transmit heat. He found as many gradations to exist in bodies with regard to this property, as with regard to transparency. In the course of his researches he ascertained, that if the quantity of radiant heat transmitted through the atmosphere be estimated at 100, the following numbers will express the proportions transmitted through an equal mass of the substances named below.

Air - - - - - - - -	100
Rock salt, transparent - - -	92
Flint glass - - - - - - -	67
Bisulphuret of carbon - - - - -	63
Calcareous spar, transparent - - -	62
Rock-crystal - - - - - -	62

Topaz, brown	57
Crown-glass	49
Oil of turpentine	31
Rape-seed oil	30
Tourmaline, green	27
Sulphuric æther	21
Gypsum	20
Sulphuric acid	17
Nitric acid	15
Alcohol	15
Alum, crystals of	12
Water	11

§ 387.

Those rays of heat which are combined with flame are called *luminous thermal rays*. To this class belong the rays of heat emitted by the sun: they penetrate through all diathermanous substances. Those rays, on the contrary, are said to be *opaque*, which proceed from bodies heated below the point of active combustion: these rays are but partially transmitted by certain bodies. Melloni inferred that the rays of heat must be of different kinds, and that the transmission of them might be compared with the transmission of the rays of light through coloured bodies; for when light passes through a coloured medium, we find those rays only are transmitted which resemble the medium; all others are absorbed. Flames emit rays of heat of all the different kinds, but in unequal proportions, in this respect resembling white or solar light. The heat produced by other sources is deficient in one or more of the varieties; whence the opaque rays of heat are analogous to the rays of coloured light. Bodies are therefore either *perfectly* or *partially* diathermanous; the former transmitting all the thermal colours, and the latter only some of them. Rock salt is the only perfectly diathermanous substance; it therefore stands to heat in the same relation as absolutely transparent glass does to light. The other diathermanous substances resemble the variously coloured diaphanous bodies, which transmit light but partially.

§ 388.

The rays of heat, from whatever source derived, like those of light, are *refrangible*; *i. e.* if transmitted through a diathermanous prism, they are refracted according to laws similar to those which govern the refraction of light through a prism. (§ 300.)

From this property of the calorific rays, it follows that they may be collected in a focus, if transmitted through a diathermanous convex lens. Actual experiment has proved the truth of this; which we should have inferred, had we reasoned only from the analogy between heat and light.

It has been further ascertained, that the rays emitted by different sources of heat have a different refrangibility, and that the opaque thermal rays are less refrangible than those which proceed from luminous sources of heat. In this, again, we recognise an analogy between heat and light, the variously coloured rays of the latter having each a peculiar refrangibility. (§ 316.)

From what has been already advanced, it follows that when the various rays have passed through a diathermanous prism, they will compose a *thermal spectrum*, in like manner as the sun's rays form a solar spectrum (§ 316.): in fact, such a spectrum is made by the calorific rays, combined with the luminous rays, in the sun's beams. The thermal and chromatic spectra, however, do not exactly coincide. (§ 358.) The heating rays of greatest refrangibility bound the spectrum at about the spot where the violet and blue of the chromatic spectrum touch. From this point their intensity increases through the blue, green, yellow, orange, and red light, and even to a little distance beyond the termination of the last named colour. There it rapidly diminishes, and terminates at a distance from that point equal to one-third of the length of the spectrum. The solar spectrum represented in *fig.* 69. (as has been already mentioned in § 316. and 358.) shows also the extent of the thermal spectrum; the fine curved line exhibiting the intensity of the different colours, and the dark line the intensity of the different heating rays, which, however, as Seebek discovered, varies according to the material of which the prism consists. The proportions depicted in the diagram referred to are those given by a prism of rock salt.

We have mentioned in the preceding section that rock salt is the only absolutely diathermanous substance with which we are acquainted; as therefore, in our experiments on the refraction of light, we always make use of glass prisms and lenses, so in experiments on the refraction of heat we must employ rock salt; all other diathermanous substances being, in regard to heat, what coloured glass is to light. A convex lens of rock salt may therefore be used to collect all the rays into its focus; and a burning glass, of so deep a violet as to be almost opaque, will produce a far stronger heat, by collecting the rays emitted from burning coals, or any other heated body, than we should obtain by using a common burning glass of equal size. The glass may be rendered of the desired hue by means of manganese.

§ 389.

Lastly, Forbes and Melloni have recently proved, experimentally, that heat, as well as light, is susceptible of *polarization*, *double refraction*, and *interference*.

Forbes also experimentally verified the truth of Fresnel's theory, that the waves of heat are greater than those of light; he found them to be about thrice as long as the waves of red, and 4½ times as long as the waves of violet light. Consequently, the vibrations made by the waves of heat will be, in the same ratio, more slow than the waves of light.

If we regard the series of facts on which our knowledge of the radiation of heat is founded, we cannot avoid the conviction, that in its propagation, velocity, reflection, refraction, and polarization, so strong a resemblance exists between it and light as amounts almost to an identity. But if in these respects these two mighty physical agents seem to obey the same laws, and to be subject to the same modifications, through the action of ponderable matter upon them, yet the analogy holds good only so long as their rays move freely; for the difference between light and heat is wide indeed, when radiation is interrupted, either at the surface or in the interior of a body.

The experiments by which Forbes and Melloni arrived at a knowledge of those properties in radiant heat which we have glanced at in the preceding sections, require for their performance costly apparatus; the experiments themselves are extremely delicate and difficult, for which reasons they are not adapted for performance in schools and colleges; a more detailed account is therefore omitted in the present treatise.

B. *Conduction of Heat in Bodies.*

§ 390.

When heat has penetrated into the interior of any body, it endeavours to diffuse itself so as to bring all parts of the body to an equal temperature. The rate at which this equalization is brought about, is the measure of a body's *conducting power*. Substances are divided, accordingly, into *good* and *bad* conductors of heat; the former class comprising such as propagate heat rapidly, and the latter such as diffuse it slowly throughout their mass. Heat is conducted more quickly, the greater the difference of temperature between the bodies, or parts of a body, that are in contact.

The following simple experiment will illustrate the truth of the last remark: —

Expt. Plunge the bulb of a thermometer into hot water: at first the ascent of the mercury in the tube will be very rapid; but the nearer the temperatue of the metal approximates to that of the water, the smaller its expansion.

Experience proves that heat is capable of being diffused throughout all substances, without exception, and that no material exists which can exclude it.

§ 391.

It has been found, by numerous experiments, that *the conduction of heat in the interior* of bodies, both solid, liquid, and gaseous, is regulated by the same law; but that equal volumes require very unequal times, according to the conducting power of the particular substance; and that, generally speaking, the denser any body is, the better conductor of heat does it become. This equalization of temperature is considerably modified in liquids and gases, by the extreme mobility of their particles.

In solid bodies heat extends itself from the particle in immediate contact with the source of heat to the next particle; from it again to the next, and so on, until the whole mass has acquired the same temperature. The best conductors of this class of substances are the metals, but among them there exists a great diversity in this respect. Metals in an oxidized state, as they are found in most stones, glass, burnt clay, &c., have a mean conducting power. Organic bodies are bad conductors of heat; as instances, we may mention cork, straw, charcoal, ashes, cotton, wool, silk, hair, feathers, &c.

Rumford considered that these porous bodies were bad conductors of heat, in consequence of the portion of air in a quiescent state contained in their interstices. Heat travels more slowly, in proportion as it passes frequently out of one substance into another, of different densities.

Despretz has represented the conducting powers of various bodies by the following numbers: —

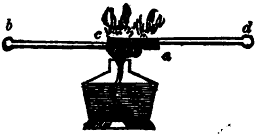
Gold - - -	10,000	Tin - - -	3,039
Silver - - -	9,730	Lead - - -	1,796
Copper - -	8,980	Marble - -	236
Platina - -	3,810	Porcelain - -	122
Iron - - -	3,743	Tile - - -	114
Zinc - - -	3,630		

Woods are among the substances that have the lowest conducting power. De la Rive arranges them in the following order: nut, oak, fir, poplar, cork. He considers, also, that they all conduct heat better in the direction of their fibres than across the grain.

The following simple experiment will at once show the inferiority of glass to metal as a conductor of heat: —

Expt. Let *a b*, *fig.* 109., be a piece of brass, copper, or iron wire; and *c d* a piece of glass of equal size and length. Tie both the rods firmly together at one end by a bit of wire, and put a ball of wax at their other extremities. Heat the apparatus by applying to it the flame of a spirit lamp; and the wax at *b* will be completely melted, whilst that at *d* is unchanged.

Fig. 109.



§ 392.

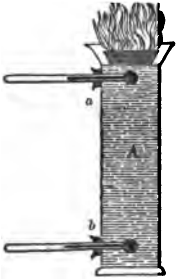
The propagation of heat in non-elastic fluids varies according as it is applied from above or from below. If heat be applied at the upper surface, the conduction proceeds just as in solid bodies, and in this case liquids prove themselves very bad conductors of heat; but if heated from beneath, their particles rise successively to the upper surface, their elevated temperature rendering them specifically lighter than the cooler particles above them; the greater weight of which causes them to descend and take the place originally occupied by the others. Thus, a constant current is excited in any liquid heated from beneath, by which the conduction of heat throughout its mass is greatly accelerated. The process is exactly reversed if a fluid be cooled from above or from beneath.

The following experiments may serve to confirm the truth of the above remarks: —

First Expt. Partly fill a tall glass vessel with water, and throw in a little roughly-powdered amber; heat the water by a spirit lamp, and the current in the fluid will be rendered visible by the ascent of the particles of amber up the middle of the fluid, but on their approach towards the sides of the vessel, they will sink again with the cooler particles of the water.

Second Expt. Let A, *fig.* 110., be a vessel made of plates of iron or tin; near the bottom of one of its sides insert a thermometer *b*, and also a second thermometer at *a*, near the top of the vessel. Fill it with water just above *a*; *c* is a thin metal cup floating on the surface of the water, which is to be filled with spirit of wine or sulphuric æther; light the spirit, or, if you please, fill the cup with as much hot sand as it can carry, and the heat produced by it at the surface of the water will very soon be shown by the thermometer *a*: the thermometer at *b* will meanwhile be scarcely affected by it.

Fig. 110.



Place the vessel on a lump of ice, and the lower thermometer will in a little time mark a change of temperature, but the thermometer *a* will not indicate any alteration till long after.

In both these cases water is shown to be a bad conductor of heat.

When the temperature of the water at the lower part of the vessel has fallen to about 39° Fahr., the water rendered lighter thereby begins to ascend (§ 376. obs.), and the warmer water above to descend and take its place.

Now place the vessel on a hot brick, and conduction will take place from the bottom, the elevation of the temperature will speedily be observable in both the thermometers. The water beneath being heated is rendered lighter, and rising rapidly, it acts on the upper thermometer.

Lay a piece of ice on the surface of the water, and both the upper and lower thermometers will quickly indicate a decrease in the temperature. The water on the surface, as it cools, becomes also heavier, and as it descends it affects the lower thermometer.

In the torrid and temperate zones the temperature of the sea will diminish as the depth below the surface increases, but in the frigid zones the reverse will happen, for as the temperature at the surface is less than 32°, the lower strata cannot have a less degree of warmth than 39°. Hence the formation of ice always begins at the surface; were the change of form in water to begin at the bottom, the whole mass would be converted into ice.

Aeriform bodies closely resemble the non-elastic fluids in the conduction of heat, these two classes of bodies being distinguished by the readiness with which their particles move among each other, and both having the same conditions of equilibrium. Air, in a tranquil condition, is a very bad conductor of heat, but when agitated, it promotes the propagation of heat, more quickly even than liquids, by the more rapid ascent of its heated particles.

To this property of air we must attribute the motions in our atmosphere, noticed already in the observation to § 206.

By referring to the unequal power various bodies possess for conducting heat, we can explain many circumstances that come under our notice in our ordinary experience. Thus, *to communicate heat quickly* we must make use of such substances as are *good conductors;* if we desire, on the contrary, *to retard* its operations, we must select such bodies as are *bad conductors.*

From what has been already stated, the student will be able at once to answer the following queries, and to explain the technical uses of the various conducting substances.

Why do brass cannon become hot more readily than iron? If we touch a piece of wood and a piece of metal both at the same temperature, the latter feels colder than the former, if the temperature be lower than that of our own body; but if the temperature of these substances be higher than that of our bodies, then the metal feels hotter than the wood. Water is made to boil sooner in metal vessels than in earthenware. Wooden walls and thatched roofs are cooler in summer and warmer in winter than brick walls and tiled roofs. Wool, feathers, and fur are a better protection against inclement weather than several wraps of linen or leather. Snow is one of the worst conductors of heat. Utility of this property.—If our bodies come in contact with water and quicksilver, the sensations they excite are precisely similar to those caused by touching wood and metal. Use of making boilers, saucepans, and similar vessels, with wide bottoms. Use of double windows.

IV. CAPACITY FOR HEAT.—SPECIFIC AND RELATIVE HEAT OF BODIES.

§ 393.

Similar bodies require *an equal quantity of heat* to raise them from any given temperature to a higher.

First. Expt. This may easily be proved by placing two equal cups of like material on the hob of a stove in which there is a fire; let each of the cups contain an equal quantity of water of the same temperature; each cup, therefore, contains the same quantity of heat. After a time the water will be found to have become hotter, but the temperature of that in each of the vessels will still continue equal.

If we assume the quantity of caloric requisite to raise 1lb. of water 1° above the freezing point for our unit of measurement, then we should require 20 times as much to raise 1lb. of water from 32° to 52°, or 120 times as much to raise 6lbs. the same number of degrees.

If similar substances of unequal magnitude or masses have the same temperature, *the quantity of free caloric they contain will be proportional to their masses.* If, on the contrary, they have different temperatures, and they are brought into contact, or are mixed together, then the free caloric is equally distributed throughout the whole mass.

Second Expt. Mix together 1lb. of water at 52° and 1lb. at 72°, and you will obtain 2lbs. at $\frac{52+72}{2} = 62°$.

If their masses are unequal, their common temperature after combination is found by dividing the sum of the products of their masses into their temperatures by the sum of their masses, thus, *ex. gr.* mix 2lbs. of water at 95° with 3lbs. at 50°, and the compound will have a temperature of $\frac{(2 \times 95) + (3 \times 50)}{2 \times 3} = 68°$. — Practically, some portion of the heat will be absorbed by the vessel.

If you put M and m for the masses, T and t for the temperatures of the bodies, and x their common temperature after contact or mixture, the general expression will be

$$x = \frac{M\,T + m\,t}{M + m}.$$

§ 394.

If the temperatures of two dissimilar substances be raised to the same degree, experience proves that some substances require more and others less heat.

Expt. Place side by side upon a hot plate two equal similar vessels, one containing a certain quantity by weight of water, and the other an equal weight of mercury, If both the fluids stand at the same temperature, it is clear, under the circumstances supposed, that each vessel contains an equal quantity of caloric; after a very short time, however, we shall find that the mercury has become much hotter than the water.

In like manner, it has been found in lowering the temperature of dissimilar substances to an equal degree, that some give out more and others less caloric.

Hence it follows, in most cases, that if two dissimilar substances whose masses or weights are equal have the same temperature, they contain unequal quantities of heat.

We attribute, therefore, to bodies a different degree of susceptibility for receiving free caloric into their interior structure, or within their molecules; this is called their *capacity for heat*, and the quantity required to raise equal masses or equal weights, 1° is termed their *specific heat.* It has also been determined, that a certain relation subsists between the density of bodies and their capacity for heat, this capacity in general being less, the denser the structure of the substance.

If we determine the specific heat of different substances, we can compare their respective capacities for heat. To do this intelligibly with regard to all bodies whatever, we must proceed in much the same manner as we did to ascertain their specific gravities. (§ 173.) The unit assumed for this purpose is the capacity of a certain weight of pure water. Equal masses of other substances are compared with this unit thus: if their capacity for heat exceed that of water, by numbers greater than 1; if it be less than that of water, by fractional quantities.

The specific heat of bodies has been determined, not only for equal weights, but also for equal volumes, and this is called their *relative heat*, which is to the specific heat of any body directly as its specific gravity. It may be found by multiplying the specific heat into the specific gravity; and conversely, the specific heat may be found by dividing the relative heat by the specific gravity.

It has been found by experiments, which will be detailed in the next section, that the quantity of heat requisite to raise the temperature of 1lb. of water 1°, would suffice to raise 1lb. of quicksilver 33°. If, then, we assume the quantity required for water as unity, the specific heat of mercury will be $\frac{1}{33}$; and since (Tab. IX. p. 187. Vol. IV.) the specific gravity of mercury is about 13·6, it follows that the relative heat of an equal volume of this metal is $\frac{1}{33} \times 13{\cdot}6 = 0\ 4121$.

Let s represent the specific gravity, c the specific heat or the capacity of the body for heat, then $r = s\,c$ will be the general expression for the relative heat of bodies, or the quantities of heat they contain with equal volume. The following table exhibits at one view the specific and relative heat of some of the principal solids and liquids.

With regard to gaseous bodies it has been found, that, whether single or mixed, their specific heat is inversely as their specific gravity or density, and, consequently, equal weights of such gases contain a larger quantity of heat the less their specific gravity. But further, as the relative weights of equal volumes of gas are inversely as their specific gravities, it follows that equal volumes of these gases will have equal relative heat; *i. e.* they will contain equal quantities of caloric, in fact, the same as atmospheric air itself. Chemically combined gases, on the contrary, have a different relative heat from such as are simple or merely mixed; their relative heat exceeds that of common air, and each such gas has a distinct index to express its relative heat; so the quantity of caloric they contain exceeds that contained in an equal volume of atmospheric air.

The capacity of atmospheric air is assumed as the unit by which to estimate the specific heat of gaseous bodies; but sometimes that of water is assumed as the unit, and then the capacities of these bodies are comparable with those of solids and liquids. The latter values are obtained by multiplying the former into 0·2669, which is the index of the specific heat of atmospheric air as compared with that of water.

In Table XI. the capacity of most gases will be found for equal measures both by weight and volume.

TABLE XI.

Of the Specific and Relative Heat of Bodies, and the Ratio of their Specific Heat to their Atomic Weights.

Name of the Substance.	s. Specific Gravity.	a. Atomic Weight according to *Berzelius*.	c. Specific Heat.	r = sc. Relative Heat.	n = ac. Constants to the Atomic Weight Mean value = 40.	$\frac{ac}{40}$.
Simple Substances.						
Bismuth - - -	8·716	886·92 (?)	0·03084 Regnault	0·2744	27·353 (?)	0·7 (?)
Lead - - -	11·330	1294·50	0·03140 —	0·3558	40·647	1·
Platinum - -	20·855	1233·50	0·03243 —	0·6765	39·933	1·
Gold - - -	19·240	1243·01	0·03244 —	0·6241	40·328	1·
Mercury - - -	13·800	1265·22	0·03332 —	0·4596	42·149	1·
Antimony - -	4·450	806·92	0·05077 —	0·2256	40·944	1·
Silver - - -	10·474	1351·61 (?)	0·05669 —	0·5938	66·645 (?)	1·7 (?)
Tin - - -	7·291	735·29	0·05695 —	0·4148	41·345	1·
Arsenic - - -	5·760	470·04	0·08140 —	0·4689	38·261	0·95
Copper - - -	8·257	395·70	0·09515 —	0·7855	37·849	0·94
Zinc - - -	7·038	403·23	0·09555 —	0·6723	38·526	0·96
Iron - - -	7·497	339·21	0·11379 —	0·8475	38·597	0·96
Carbon (Diamond) -	3·515	76·44 (?)	0·14687 —	0·5160	12·227 (?)	0·3 (?)
Sulphur - - -	1·950	201·17	0·20259 —	0·3940	40·754	1·
Phosphorus - -	1·735	196·14	0·25142 —	0·4362	37·024	0·94
Compound Substances.						
Liquids						
Alchol - - -	0·793	—	0·62200 Despretz	0·4932		
Oil of Turpentine -	0·841	—	0·42593 Regnault	0·3583		
Linseed Oil - -	0·940	—	0·52800 Kirwan	0·4963		
Water - - -	1·000	—	1·00000	1·0000		
Muriatic Acid - -	1·153	—	0·60000 Dalton	0·6918		
Nitric Acid - -	1·330	—	0·68000 —	0·9044		
Sulphuric Acid -	1·834	—	0·35000 —	0·6454		
Solids						
Charcoal - -	0·360	—	0·24111 Regnault	0·8676		
Oak - - -	0·677	—	0·51000 Mayer	0·3453		
Ice - - - -	0·921	—	0·90000 Kirwan	0·8289		
White Wax - -	0·969	—	0·45000 Gadolin	0·4361		
Coal - - -	1·370	—	0·19230 Crawford	0·2630		
Coke - - -	—	—	0·20001 Regnault	—		
Graphite - -	2·000	—	0·20187 —	0·4037		
Crown Glass - -	2·450	—	0·20000 Irvine	0·4900		
Flint Glass - -	2·452	—	0·19000 Dalton	0·6540		
Cast Iron - -	7·251	—	0·12500 Despretz	0·9060		
Brass - - -	8·200	—	0·09391 Regnault	0·7700		

GASES.

(*This Table is taken from Baumgartner's Naturlehre,* 7 *Aufl. p.* 669.)

Name.	S. Specific Gravity.	a. Atomic Weight.	c. Specific Heat with equal Weight.		r = sc. Relative Heat with equal Volume.	n = ac. Constants to the Atomic Weight = 24.	$\frac{ac}{24}$.
			Air = 1	Water = 1			
Atmospheric Air	1·0000	—	1·0000	0·2669	1·000		
Oxygen	1·1026	100	0·9069	0·2421	1·000	24·21	1·
Hydrogen	0·0688	6	14·5348	3·8793	1·000	23·28	0·97
Nitrogen	0·9760	88	1·0318	0·2754	1·000	24·20	1·
Carbonic Oxide Gas	0·9569	176	1·0267	0·2740	1·000	48·22	
Protoxide of Azotic Gas	1·5269	277	0·8035	0·2145	1·227	59·28	
Carbonic Acid Gas	1·5240	276	0·8195	0·2187	1·249	60·17	
Olefiant Gas	0·9852	89	1·7898	0·4777	1·754	42·45	
Steam at 212°	0·6235	112	3·1360	0·8370	1·960	93·74	

§ 395.

The following methods have been adopted for determining the specific heat of different substances: —

1.) By means of *mixing* them. — According to this mode the substance under investigation is raised to some particular temperature, and is then poured or plunged into an equal weight of water or some other fluid. The temperatures of the two substances thus mixed or brought into contact after some time become equalized; *i. e.* the free caloric in the two bodies establishes an equilibrium. Their mutual capacities for heat are determined by the decrease in the temperature of the hotter body and by its increase in the cooler.

First Expt. If 1lb. of quicksilver at 32°, and 1lb. of water at 66°, be mixed together, the common temperature will be 65°. — The temperature of the metal has therefore risen 33°, whilst that of an equal quantity of water has fallen 1°.

Had the mercury been at 66°, and the water at 32°, the common temperature of the mass would have been 33°; in this case the water would have gained 1° of heat, and the mercury would have lost 33°.

From each of these experiments it appears that the capacity of water for heat exceeds that of mercury 33 times, if the former be assumed = 1, the specific heat of the latter will be $\frac{1}{33}=0·033$.

Second Expt. Throw one pound of iron-filings at 68° into 1 lb. of water at 32°, and the mixture will stand at 36° as soon as equilibrium is established. — That quantity of heat therefore, the loss of which lowers the temperature of iron 32°, produces a rise in the temperature of water of only 4°; whence it is evident that eight times as much caloric is requisite to raise or depress the temperature of the water 1°, as would raise or depress the temperature of an equal weight of iron 1°. Hence we infer the specific heat of iron to be $\frac{1}{8}$ or 0·125.

Expressing this law in general terms, let M be the weight of a mass of water, t its temperature, and C its capacity for heat; let m be the weight of the hotter substance which is to be examined, T its temperature, c the capacity sought, and T′ the temperature of the mass when mixed.

Then the quantity of caloric gained by the water will be $MC(T'-t)$; for it is obvious that the quantity of heat necessary to raise the temperature of a body any number of degrees must be proportional to its mass and capacity. In like manner the amount lost by the body under investigation may be expressed by $mc\ (T-T')$. But as both these expressions are equal to each other,

$$MC(T'-t) = mc(T-T');$$

$$\therefore \frac{c}{C} = \frac{M(T'-t)}{m(T-T')};$$

and putting the capacity of water $=1$, the specific heat of the body under investigation will be

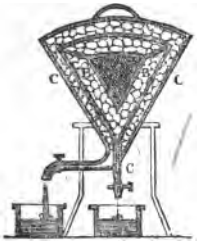
$$c = \frac{M\ (T'-t)}{m\ (T-T)};$$

This method, adopted by De Luc, Crawford, and other philosophers, is not altogether free from inaccuracy, as during the experiment a portion of the heat is necessarily lost by radiation, as well as by conduction to the vessel and to the ambient air.

2.) The capacity of substances is found by observing the *quantity of ice* the body under investigation is capable of thawing. This experiment is best performed by placing the substance in a *calorimeter*, and so completely surrounding it with ice.

The calorimeter (*fig.* 111.) consists of a vessel of tin or iron plates C, enclosing a smaller one B, and inside this is a wire-cage A, intended to contain the substance to be examined. The space between the first and second vessels, as well as that between the second and third, is filled with

Fig. 111.



pounded ice. The ice in the outer space prevents the warmth of the external air from acting on the substance within, so that the ice around the wire cage is affected only by the heat emitted from the substance under investigation, which continues to thaw the ice until its own temperature is lowered to 32°. The water thus generated escapes by a cock *c*; at the close of the experiment it is weighed. To obtain the specific heat of liquids we must put them into vessels of known specific heat.—The principle on which this apparatus acts is this, that melting ice maintains invariably the temperature of 32° Fahr., and that all the heat applied to it is expended solely in thawing it.

From experiments which will be described in the next division of this subject (§ 402. expt. 2.) it has been ascertained that 135° of heat are necessary to melt 1lb. of ice; whence the mass of M lbs. of ice (equal to the weight of the water discharged) melted in the calorimeter must have deprived the body in the wire-cage of M times 135° of heat. Call the mass of this substance *m*lbs., its temperature above 32° when placed in the calorimeter t°, and its capacity *c*, then the quantity of caloric it contained would be $m\,t\,c$; but $m\,t\,c = 135\ \mathrm{M}$; whence the capacity sought is

$$c = \frac{135\ \mathrm{M}}{m\,t},$$

ex. gr. 2lb. of iron at 122° in cooling to 32° melts $\frac{1}{6}$lb. of ice; whence

$$c = \frac{135 \times \frac{1}{6}}{2 \times 90} = \frac{1}{8}.$$

This method, which was adopted by Lavoisier and La Place, is available for solids and liquids; it gives results more accurate than the former, but requires extreme precision in conducting the experiment.

3.) *By cooling the substance.* The principle on which this method depends is this — that the more slowly a body cools the greater must be its capacity for heat; for it must have parted with a greater quantity of caloric, to give out which the longer space of time was required. In this case it is necessary to enclose the substance to be examined in a shell which has the same constant radiating power.

To effect this, the body which is the subject of our investigations is placed in a pulverized or fluid condition in a polished metal receiver (a cylinder of thin silver is best), and the time is noted which elapses before it falls from some particular temperature any certain number of degrees. If one substance cool as rapidly again as another, then the relative heat of the former is only half that of the latter; whence by the preceding section we can readily find the specific heat.

This method was first invented by Mayer, it was subsequently improved upon by Leslie, and has been carried to a high degree of perfection by Dulong and Petit.

The specific heat of gases cannot be ascertained by any one of the three methods yet described. Delaroche and Bérard used for this purpose *Rumford's water-calorimeter*, a vessel filled with water through which a spiral tube is conducted. The gas to be examined is well dried and is then brought from a vessel surrounded with boiling water at 212° gradually through the worm of the calorimeter, from the open end of which it escapes. In the course of its passage the gas parts with a portion of its caloric to the cold water which surrounds the worm, the temperature of this fluid gradually rises until after the lapse of some time it becomes stationary. The equilibrium thus established between the water and the gas is measured by means of a thermometer, so that we find both the rise in the temperature of the water and the fall in that of the gas. Now, if the experiment be repeated with some other gas, and the result should give a higher temperature to the water, then this second gas must have imparted to the fluid a greater amount of caloric than the former one did; if, on the contrary, the temperature of the water be less this time than before, it will have given out less caloric, and the respective capacities for heat of these two gases will be proportional to the temperatures of the water through which they have been conducted. If the capacity of atmospheric air be assumed as the unit, the specific heat of other gases may be expressed by proportionate numbers.

To raise 1 lb. of water from 32° to 212° we require the same quantity of heat as would have raised 4 lbs. of atmospheric air the same number of degrees. The specific heat of air is therefore ¼th, or more exactly 0·2669, that of water.

§ 396.

The capacity of both solids and liquids is not constant, but varies with every change in their density. Their capacity increases when the density decreases, and vice versâ, whether this variation be caused by mechanical means, or by a rise or fall in the temperature of the body, but in a less degree than their original value, that is to say, more caloric is requisite to raise a body from 212° to 213°, than from 32° to 33°. This increase in a body's capacity for heat may be accounted for on the assumption, that but a part of the heat gained by the body tends to elevate its temperature, and that the remainder is consumed in effecting the change in its volume.

Dulong and Petit, found as a mean of numerous experiments the capacity of

	From 32° to 212°	to 572°.
Mercury	0·0330	0·0350
Platina	0·0335	0·0355
Antimony	0·0507	0·0549
Silver	0·0557	0·0611
Zinc	0·0927	0·1015
Copper	0·0949	0·1013
Iron	0·1098	0·1218
Glass	0·1770	0·1900

In like manner the capacity of coal and charcoal diminishes as its density increases. Regnault found that of

Charcoal	0·2415
Coke from Cannel coal	0·2030
Black lead from gas retorts	0·2036
Diamond	0·1468

The capacity of gases for heat varies in the same manner as that of solids and liquids, viz. it increases when they are rarefied, and diminishes when they are condensed; it diminishes therefore when they are subjected to an increased pressure; but these variations are not correspondent to the degree in which the condensation or rarefaction obtains. For atmospheric air, for instance, acquires only one-tenth greater capacity for heat when its pressure is reduced one half, and it must be rarefied 18 times, in order to double its capacity; if the air be condensed this capacity will be diminished in the same ratio as it was increased in by rarefaction. In order to elevate the temperature of any quantity of gas 1°, supposing it to be perfectly free to expand, and that the pressure on it remains constant, a larger amount of caloric will be needed than if it were constrained by pressure to retain its volume unaltered; *i.e.* in other words, *the specific heat of gases at a constant pressure exceeds their specific heat when their volume is permanent.*— Dulong found by experiments based on the different velocities with which sound travels in gases of different densities, that in the case of the simple gases and their compounds, the ratio between their specific heat under the same pressure and with the same volume is as 1·421 to 1.

If, now, we assume the caloric required to raise the temperature of a certain quantity of gas 1°, its volume remaining the same, as unity, 1·421 will represent the caloric, which would produce an equal elevation of temperature, if the gas could expand freely under its original pressure. Next, let us suppose the caloric needed in the latter case to be divided into two portions, one of which raises the temperature of the gas 1°, and the other 0·421 causes the expansion answering to that particular temperature. This latter portion of heat must consequently be set free again if the gas be compressed as much as it had previously expanded itself. If, therefore, we know the index of any gas's expansion, we may from it deduce the quantity of heat which will be set at liberty by its compression into smaller limits. Now (since § 377.) the index for the expansion of atmospheric air each degree above 32° is $\frac{11}{5400}$, or 0·002037; its temperature will be 0·421°, if it be compressed 0·002037 of its volume; if it be compressed to $\frac{1}{10}$th its volume, the temperature will be $32 + \frac{0{\cdot}1}{0{\cdot}002037} \times 0{\cdot}421 = 52{\cdot}7^\circ$; if to $\frac{1}{2}$ its volume, the temperature will rise to $32 + \overline{5 \times 20{\cdot}7} = 135{\cdot}5^\circ$.

§ 397.

In the investigations undertaken by Dulong and Petit for determining the specific heat of bodies, they at once discovered that it appeared to stand in a simple relation to their atomic weights. (§ 63.) In the simple substances, with but few exceptions, it was inversely as their atomic weights, so that by multiplying these two magnitudes a pretty constant number was obtained, which, according to Regnault's latest investigations, lies somewhere between 38 and 42. This comes pretty nearly to the law laid down by Dulong and Petit, that *the atoms of all the simple substances have an equal capacity for heat.* Naumann's and Regnault's discoveries have led to the further belief that *the specific heat of all compound bodies which are composed of an equal number of single atoms, and these combined in one and the same manner, is inversely to their specific gravity,* or that the products of the specific heat of all such bodies into their specific gravities are equal. These products evidently express the quantity of heat which must be imparted to raise the temperature of one atom of the particular compound 1° above 32°; whence *the atoms of the elements themselves, as also bodies similarly combined both atomically and chemically, at equal temperatures contain equal quantities of caloric.*

We have already said that Regnault's investigations led him to estimate the mean value of the constant for the elementary substances at 40, the same philosopher found the constant for the following compounds, viz. : —

Oxides.

$RO = 70$

$R^2O^3 = 170$

$RO^2 = 86$

Sulphurets.

$RS = 74$

$R^2S^3 = 191$

$RS^2 = 129$

Chlorides.

$R^2Cl^3 = 159$

$RCl^2 = 117$

$RCl^4 = 230$

Nitric-acid Salts.

$N^2O^5 + RO = 302$

Sulphuric-acid Salts.

$SO^3 + RO = 166$

Carbonic-acid Salts.

$CO^2 + RO = 134.$

In these chemical formulæ R stands for the number of atoms contained in the base, the other letters are the symbols generally used to express those particular elements.

The specific heat of any substance may be estimated approximately by dividing the mean constant by its atomic weight.

Thus, for instance, we find the specific heat of those simple substances whose mean constant is 40, as iron, the atomic weight of which is 339 (see Table IV. p. 63. Vol. I.), 40 : 339 = 0·118; that of lead, whose atomic weight is 1294, 40 : 1294 = 0·0309; that of sulphur, whose atomic weight is 201, 40 : 201 = 0·199.

§ 398.

We have already stated that the capacity of a body for heat does not remain constant (§ 396.); it has also been ascertained that this capacity may be affected by various causes. As soon as any change occurs in the capacity of any body for heat, the equilibrium of its free caloric is disturbed; if the capacity be diminished, caloric is set at liberty; if it be increased, that heat which was sensible becomes latent, and the temperature of the substance is lowered.

The chief causes which induce a change in the capacity of a body for heat are the following: —

1.) *A change in its volume,* which invariably attends every rise or fall in the temperature of a body. (§ 363.) A diminution in the bulk of a substance lessens its capacity for heat; pressure therefore will have this effect: on the contrary, expansion is attended by increased capacity.

These two results are most perceptible in gases, these substances admitting of the most rapid and extreme compression and expansion. The following experiments may illustrate the above remarks: —

First Expt. Tinder or touch-wood may be ignited by the rapid condensation of the air in the Tachopyrion. This instrument in the main consists of a hollow cylinder of glass or brass, open at one end but closed at the other, its length being from 6 to 10 inches, and its width from 3 to 4 lines. An iron rod furnished with a solid piston works accurately up and down; when thrust to its utmost it does not quite reach the bottom of the tube. To the under side of the piston a little hook is fixed on which a small piece of touch-wood is fastened. The piston is then worked up and down as quickly as possible, that the spark in the tinder may not be extinguished immediately, as the small quantity of oxygen contained in the condensed air soon becomes exhausted. Ignition happens when the air has been condensed to about one-fifth of its original bulk, and as 550 degrees of heat are needed to produce combustion in the touch-wood, it follows that this quantity of heat is set at liberty by the condensation of the air.

Second Expt. A delicate air thermometer, placed under the exhausted receiver of an air pump, sinks as rarefaction progresses, and rises again on the re-admission of air.

Gases, powerfully condensed on their efflux from small apertures, produce a considerable degree of cold in consequence of their expansion.

Third Expt. Procure a cylindrical vessel made of sheet-iron, about one line in thickness, so put together as to be perfectly air-tight; let its ends be nearly hemispherical; let it be furnished with a cock, and by means of a condensing pump (§ 187.) condense the air within till it amounts to thrice the density of the atmosphere: turn the cock so as to allow of the escape of the air, and the cold generated by its efflux will be sufficiently great to freeze water, supposing the dimensions of the vessel to be not less than 6 inches by 18. The hole in the cock should have a diameter of not less than half a line. To ensure the success of the experiment tie a small hank of cotton, saturated with water to the end of a stick, and expose it to the current of air.

Air condensed, less powerfully than in the above experiment, produces a degree of cold appreciable by an air thermometer.

Hence we see why breath expelled gently from the mouth is warm, whilst a strong expiration is cold.

As liquids are compressible in a very low degree, the consideration of heat produced by compression is extremely difficult, and the results yet obtained are by no means satisfactory.

It is universally known that solid bodies become hot by sudden condensation, as *ex. gr.* iron when hammered. This elevation in their temperature may be regarded, at least in part, as owing to their diminished capacity for heat.

2.) *A change in their form of aggregation.* Bodies which are capable of assuming different forms of aggregation display various capacities for heat, according to the condition in which they exist. The molecular forces in operation among the constituent particles of the body are placed in a new relation to each other as regards their intensity (§ 13.), and thus probably the susceptibility of the body for heat is modified.

Thus, *ex. gr.*, it has been ascertained that the capacity of ice for heat is 0·9; of water, 1, and of steam, 0·8. This specific heat is not to be confounded with that caloric which brings about the change of form in the body; that subject will be treated of more at length in the next section.

3.) *A change in the chemical constitution of the substance.* When two bodies combine chemically, their aggregate form frequently undergoes a change; and even when this is not the case, as when two liquids are combined, yet their individual properties are altered, and in most instances heat is produced, though in others the temperature of the mass is lowered.

Fourth Expt. Pour sulphuric acid into water; the mixture will show a considerable elevation in temperature. The capacity of the compound for heat must therefore be greatly less than that of its component elements.

A similar effect obtains when water is poured on lime (slacking lime).

If, on the contrary, salt and pounded ice, or snow, be mixed together, the temperature of the compound is greatly lowered; hence we infer that its capacity for heat is increased.

V. HEAT PRODUCES A CHANGE IN THE AGGREGATE FORM OF BODIES.

§ 399.

From what has already been established, we know that the volume of any substance is enlarged by raising its temperature, and decreased by lowering the temperature. (§ 373.) Expansion weakens the cohesion between the particles; condensation, on the contrary, increases this force. Both these changes can however, in many bodies, take place only within certain fixed limits; when they are exceeded, *a change ensues in the aggregate form of the body itself.*

The following are the most important facts that have been observed with regard to this process: —

When the temperature of a body is raised, it assumes that new form of aggregation in which its cohesion and density are lessened, and the repulsive force among its atoms acquires a greater power, as compared with the attractive force; hence solid bodies become liquid, and the latter are changed into gases. (Compare § 13.) The temperature of the body does not become elevated, in consequence of the continued application of heat, when the period for this transformation arrives, until the entire mass has assumed its new form.

Hence we are warranted in laying it down as a general law, that *when bodies pass from the solid to the liquid state, or from the liquid to the gaseous, a certain portion of the heat becomes inappreciable either by our sense of feeling or by the thermometer; and the portion of heat thus combined with the body in its new form is said to be latent.*

Conversely, when the temperature is lowered, bodies assume that form of aggregation in which their cohesion and density are increased, and in which the attractive force among their molecules acquires a greater ratio, as compared with the repulsive force; that is to say, aëriform bodies become fluids, and non-elastic fluids are converted into solids. When this change commences, the depression of the temperature is suspended; heat is, however, parted with uninterruptedly, until the entire mass has acquired its new form of aggregation.

Hence we deduce, as a general law, that *when a gas is converted into a liquid, or a liquid into a solid, the same quantity of caloric is disengaged as was held in a latent state by the body before its change of condition.*

§ 400.

Heat or caloric in the *latent* state may be regarded as an essential element, *chemically combined* in some definite proportion with the atoms of a body; or we may, if we please, consider the substance of the body as soluble in heat. We may therefore suppose that all ponderable bodies contain certain quantities of caloric in a latent state; that solids have the smallest proportion of it; non-elastic fluids, more than solids; and gases more than either of the other kinds of bodies. When thus latent, caloric loses the power of acting externally, and affects neither our touch nor the thermometer.

That heat is spoken of as *sensible*, which is *not chemically* combined with matter, but which is supposed to be attached to it merely *mechanically*, perhaps by adhesion to its molecules: in this state heat may exist both on the surface and in the interior of bodies. Again; this sensible heat is not united in certain definite proportions, but may be accumulated or diminished in any substance to such a degree as will not induce a change in its form of aggregation.

Lastly; it is free or sensible caloric alone which generates those changes in the volume of bodies that have already been noticed. It is sensible caloric which is perceived by our sensation, and which acts on the thermometer. In consequence of the feeble power with which it adheres to the particles of bodies, it is easily disengaged from them, and is thus radiated from one object to another. The exchange of free caloric among dissimilar bodies, at unequal temperatures, does not cease when they have all received an equal amount of it; but rather, when each object contains so much as is equivalent to the force with which it is attracted by the particular particles of the body. Hence the reason why different substances have different capacities for heat, understanding this to refer merely to sensible heat.

§ 401.

The change of solid bodies into liquids is termed *fusion* or *melting*. The temperature at which this happens varies in different substances. It is of extreme importance, in many of the arts, to know precisely the point at which certain metals are fused. Some readily pass from the solid to the liquid state; others, not until they have been raised to a white heat (1.); and some few metals, and other solid bodies, have not yet been reduced by the most intense heat to which they have been subjected (2.). Alloys (§ 66.) generally melt at a temperature below that at which their component elements are fusible. Many metals are reduced more easily by the addition of some substance of this kind (hence termed a *flux*), than when acted upon by heat in their pure state (3.). Many bodies, before they become perfectly liquid, are rendered soft, and in this state may be intimately united with each other; metals which possess this property are said to be capable of being *welded*. It is extremely difficult to determine precisely the point at which these substances are fused: this is not the case with such as pass instantaneously from the one condition to the other (4.). Some bodies evaporate on attaining a certain temperature, passing off at once into the gaseous form, without going through the intermediate state (5.). Lastly; others, chiefly of the vegetable kingdom, when heated in the atmosphere to a certain temperature, without becoming liquid, combine with the oxygen of the air, and thus form gases developing both heat and light; these substances are termed *combustibles*. (§ 77.)

1.) The point at which those bodies fuse that do not readily yield to the action of heat, has not yet been determined with certainty, on account of the unsatisfactory character of the pyrometric means which the existing state of science enables us to employ. (§ 372.) The following table gives the point at which certain of the metals most difficult of reduction are fused:—

Platina fuses at	3082° Fahr.	Clarke.
Wrought iron	2912	Vauquelin.
Steel	2552 2372	Pouillet.
Gold	2192	
Cast iron, grey	2192 2012	
Cast iron, white	2012 1922	
Copper	1922	
Brass	1859	Daniell.
Silver	1832	Pouillet.

The following are the principal metals that admit of being readily fused:—

Zinc fuses at	700	Murray.
	705	Guyton Morveau.
Lead	590	Irvine.
	592	Guyton Morveau.
Bismuth	509	Ermann.
	477	Irvine.
	480	Crichton.
Tin	512	Guyton Morveau.
	442	Crichton.
	433	Ermann.
Sodium	194	Gay Lussac and Thénard.
Potassium	162	

Of the metalloids, the following may be named: —

Sulphur melts at	-	226	Dumas.
Phosphorus	- -	100	Murray.

2.) Among those bodies which are not reducible by heat, to the liquid state, are reckoned the pure earths, as calcium, aluminum, barytes, strontium, &c. In the intense heat generated by the combustion of oxygen and hydrogen, the unreducible metals, iron and platina, and several of the earths, at least in minute quantities, have been fused. Using the degree of light emitted as an approximate measure of the degree of heat, we may estimate the point of fusion at which these substances are rendered fluid in the combustion of oxyhydrogen gas, or by a galvanic current, at about 3272°.

3.) Of the alloys which liquefy at a much lower temperature than their constituent metals, it will suffice if we give one or two instances. A solder, consisting of 4 parts of lead and 6 of tin, fuses at 336°; and fusible metal, an alloy of 8 parts of bismuth, 5 of lead, and 3 of tin, liquefies at a temperature below that of boiling water. An alloy of 497 parts of bismuth, 310 of lead, 177 of tin, and 26 of mercury, melts at 162½°.

First Expt. Place a thin strip of the last named alloy in water that is almost boiling hot, and it will soon begin to melt in drops like wax.

3.) Among the *fluxes* used to accelerate the fusion of refractory metals, we may mention fluor spar. Pure iron is unreducible in the heat of the strongest furnace, but on combining with carbon, it is converted into steel, which, with the addition of phosphorus, silicium, and other substances, renders cast iron fusible. The fusion of silver is expedited by the addition of borax.

A peculiar variety of flux exists, itself capable of burning when there is an adequate development of oxygen, and at the same time generating so much heat, that small masses of the refractory metals, such as copper and silver, are melted by it. A flux of this kind may be made of 3 parts of saltpetre, 1 of sulphur, and 1 of sawdust of some hard wood.

Second Expt. Fill a nutshell with the flux just described; on the top lay a small silver coin; light the mass, and during combustion the coin will melt. As this powder does not ignite readily, it will sometimes be found advisable to sprinkle a little gunpowder on the top.

4.) Substances which become soft before they melt, and which pass from the solid to the liquid state, are very numerous. Many of them are of organic origin, and their point of fusion is below the temperature of boiling water. Some of those which are of general utility, in a technical point of view, are named below: —

Colophony begins to melt at - -	275°
Wax, brown - - - - -	110
Wax, white - - - - -	124
Tallow - - - - - -	104
Pitch - - - - - -	91

The metals which most readily admit of being welded are platina and iron; at an incipient white heat, 2372°, they become soft, and in this state portions of the metal may by pressure be made to unite intimately. The technical utility of these metals is greatly enhanced by their possessing this property.

5.) Arsenic, iodine, and camphor may be mentioned as instances of bodies that pass off in fumes on the application of heat.

Third Expt. A little piece of camphor placed in a metal or earthenware spoon and held over the flame of a spirit-lamp, soon passes off in the form of vapour.

Fourth Expt. Heat a small portion of iodine in a glass tube, about ½ an inch or an inch in width, it will not be converted into a liquid, but will pass off in beautiful violet-coloured fumes.

§ 402.

Whilst a body is actually fusing, no rise in the temperature takes place, however large the additional quantity of caloric may be that is imparted to it The increased heat is consumed in accelerating the process of fusion. The heat added to a melting substance to bring about liquefaction (§ 399.) is retained by it in a latent condition; the quantity of caloric thus made latent varies in different bodies.

Mercury contains	157°	of latent caloric.
Water - -	135	—
Tin - - -	24	—
Lead - -	10⅔	—

The knowledge we possess as yet concerning the quantity of latent heat in bodies in a state of liquefaction is extremely defective, as the results arrived at with regard to the small number of substances yet investigated are far from certain.

The following experiments will illustrate the existence of latent heat in water under certain conditions: —

First Expt. Plunge a thermometer in snow that is at a temperature *below* 32°, bring both into a warm room, and the thermometer will immediately rise; the free caloric in the surrounding atmosphere is taken up by the snow, and causes the mercury to rise; this portion of the caloric is consequently sensible. — As soon however as it has risen to 32°, the mercury is stationary, and so it continues until all the snow is converted into water, notwithstanding the additional quantity of heat absorbed by it; all this *latent* caloric is expended in liquefying the snow. — Hence we see the utility of making the point at which snow melts one of the extremes of the thermometric scale, as also why the temperature continues stationary.

Second Expt. If 1 lb. of water at 167° and 1 lb. at 32° be poured together, we shall have (§ 393.) 2 lbs. of water at 100°. — Pour 1 lb. of water at 167° on 1 lb. of ice at 32°, and you will have 2lbs. of water at 32°. — All the free caloric of the hot water has been consumed in melting the ice, and from this experiment it seems that water contains 135° of heat in a latent condition.

Of all known substances water has the greatest capacity for heat (see Table XI.), and in consequence of the great quantity of latent heat which it contains, it is a most powerful agent in equalizing the temperature of places on our earth. In consequence of this fluid's being distributed in so large a proportion over our planet, it is capable of moderating the intense heat of one part and reducing the extreme cold of another; in the former case by appropriating to itself a large portion of the caloric that is set at liberty, when a rise in temperature happens, and in the latter by giving back its heat when the temperature falls; hence we see why the variations in climate are less on the sea-coast and on islands than upon large continents, and especially in their interior. The temperature of the air under the line scarcely varies 4° throughout the year above that of the ocean : that of the water fluctuates still less, ranging between 80° and 81°. The influence of heat in its latent and free conditions is still more strongly shown in the thawing and freezing of ice in the colder regions. If water froze when the temperature fell to 32° without giving out its latent heat, all our rivers and ponds would be converted into ice on the fall of the temperature to 32°, but as water in freezing parts with such a quantity of latent heat as is sufficient to raise a mass 135 times greater than itself 1°, but a small portion becomes frozen at once, and a far larger portion at the very same time becomes warmer. As water becomes specifically lighter at a temperature less than 38¾° (Tab.

> VIII. Vol. I. p. 185.), it obeys the hydrostatic law and rises to the surface, where a coating of ice first forms itself, through which, as ice is a bad conductor, the free caloric can with difficulty penetrate. Under a mean latitude the thickness of ice never exceeds from 1 to 3 feet; under higher latitudes it is not more than from 3 to 6 feet, and even in the coldest regions it is not more than from 10 to 12 feet. Lakes and seas whose depth exceeds these dimensions are therefore never frozen to the bottom. When the ice thaws we derive an opposite advantage from this property of heat. Were not so large a portion of caloric rendered latent during the process of thawing, the entire mass of ice and snow would be dissolved as soon as the temperature rose above 32°, and the most fearful inundations would ensue; in fine, but for the latent heat of water the variations in temperature to which the earth would be subject would render it altogether unsuitable for the habitation of man.

The application of heat from an external source is not always indispensable in order to liquefy solid bodies: many substances undergo this change of form if they merely come in contact with a liquid. Nearly all the crystallized salts possess this property. If a mixture be made of one of these salts with snow, or with some other liquid, the action of these substances on each other will convert one or both of them into liquids, one portion of their free caloric being consumed in effecting this change, as also part of the heat of the vessels containing the mixture. The consequence is, that the greater the degree of cold generated during the liquefaction of the mixture, the more quickly will the liquefaction be brought about, and the greater will be the quantity of heat taken up and rendered latent by the substances composing these *freezing mixtures.*

> The following experiments will serve to illustrate the principles laid down above: —
>
> *First Expt.* Place a thermometer in a glass, into which throw some finely pulverized sulphate of soda (Glauber's Salts) and some chlorate of ammonia, or nitrate of potassa (saltpetre). — Shake the mixture and the thermometer will indicate a considerable depression of the temperature.
>
> *Second Expt.* One part nitrate of ammonia and 1 of water at 50° mixed together produce a cold of 5°; or 5 parts of chlorate of ammonia, and 5 of nitrate of potassa, with 10 parts of water at 50°, lower the temperature to 10°.
>
> These salts may be crystallized again, and they will be equally available for use.

Third Expt. Five parts of hydrochloric acid poured on 8 parts of freshly pulverized sulphate of soda reduce the temperature from 50° to 1°.

Water placed in thin glass vessels or tubes, and set in the mixtures named in this and the preceding experiment, is very quickly converted into ice.

Fourth Expt. One part of snow or pounded ice and 1 part of chloride of sodium (common salt) reduce the temperature from 32° to 1°.

Fifth Expt. Two parts of snow and 3 of finely powdered. crystallized chloride of calcium generate a cold of — 49° In this freezing mixture mercury, liquid ammonia, and æther will crystallize.

Thilorier produced an extreme degree of cold by mixing solid carbonic acid with sulphuric acid or sulphuric æther; its intensity was such that it was equal to from — 110° to — 121°. Mitchel on repeating the experiment found that alcohol of 0·798 specif. grav. at — 130° acquired the consistency of oil, and at — 146° it resembled melting wax.

To ensure success in performing the experiments described above, the following particulars must be observed:—

1.) The salts must not have lost their water of crystallization, because in that case if they are so completely dried as to be in a state of efflorescence (§ 75.) they absorb so readily the first portion of water and convert it into crystallized ice, that a considerable quantity of caloric is thereby set free; sulphate of soda is a salt that effloresces readily. 2.) The salts must be finely pulverized that they may dissolve in the fluids as quickly as possible. Above all, care must be taken that, 3.) Too much heat is not communicated from without by means of the vessel containing the mixture. To guard against this, a sufficient quantity of the ingredients must be used; and if the temperature of the ambient air be not low enough, and if it is further desirable to maintain this extreme degree of cold in the mixture for some length of time, it is necessary to fill a large vessel with some freezing mixture and to place in it a smaller vessel also filled with the frigorific substances, setting in this inner vessel the particular substance we wish to freeze. The large outer vessel should be made of some bad conductor, such as wood, clay, or the like; but the inner one in which the cold is to be generated should be made as thin as possible and of a good conductor. — Walker adopted the following neat contrivance for freezing water. His apparatus consisted of a wide tin cylinder with thick sides, enclosing a second with thin sides of equal height with the outer one. The second vessel consisted of two concentric cylinders fastened together at the bottom; in the space between these he placed the water, or whatever substance he wished to experiment on, and as he filled the innermost cylinder as well as the space between the first and second cylinders with the freezing mixture, the water or other substance was evidently enclosed completely by it. The frigorific mixture employed was that composed of chlorate of ammonia and nitrate of potassa and water given under the second experiment in this section. One advantage arising from using this compound is, that if the salts be dried by evaporation they will do for service again.

The greatest natural cold observed is that noticed by Prof. Hansteen, between Krasnojarsk and Nishne-Udinks, in 55° N. lat., which he states amounted to—55° (R. ?) = —. 91¾ Fahr. Such extreme cold is, however, not permanent at any point of the earth's surface, though at Jakutsk the mean temperature for the month of December is as low as — 44½° Fahr. In the year 1828 the cold at this place was as low as — 58° Fahr. from the 1st to the 10th of January. — The Russian army in their expedition to Chiwa endured on the Kirgesian steppe for several days together in December, 1839, a cold of —41$\frac{4}{3}$ Fahr.

§ 403.

Solidification is the condition exactly opposed to liquefaction; it is the state assumed by liquid bodies on parting with their free caloric. Without adhering rigidly to this rule, it may be observed that generally we use the term *solidification* when we speak of such fluids as become liquid at a temperature higher than that of freezing water, and *freezing* when we speak of such as become solid at a point below 32°. Most substances in passing into the solid state crystallize, if under circumstances favourable to this process, and many acquire a considerable increase in volume. According to the nature of things, the temperature at which bodies become solid is precisely that at which they liquefy. To this general law there are several anomalous exceptions. This is usually the case if the fluid which is passing into the solid form be in a state of perfect repose; and, conversely, no difference in the temperatures is found to occur if the fluid be agitated. As soon as solidification commences, a quantity of caloric is disengaged equal to that which was taken up by the body when it was converted into a liquid.

The following experiments will serve to confirm the truth of the above remarks: —

First Expt. Immerse the bulb of a thermometer in a glass of water, on the surface of which a thin film of oil has been poured, and expose the whole to a severe cold in the open air. The water continues in a fluid state, even when its temperature has fallen to 10° Fahr., provided it be not shaken. If, on the contrary, it be agitated, or if a piece of ice be dropped into the vessel, solidification commences immediately, and the temperature rises to 32°, at which point it stands till all the water has been converted into ice. The water consequently must, during the formation of the ice, have given out so much heat as suffices to raise the thermometer up to 32°. The above property was first observed by Fahrenheit.

Second Expt. Into a flask of thin glass throw 51 parts of sulphate of soda and 49 of water, so as about to fill two-thirds of the flask. Boil this mixture, and cork the bottle so as to make it air-tight at the moment when ebullition begins, and you will obtain a pretty good vacuum above the solution. The solution will retain the fluid form, even after the temperature has fallen below the point at which crystallization ought to have commenced, if the flask be kept in a steady position. Withdraw the cork, and, if necessary, drop in a small piece of the salt, in a crystalline form, and the entire mass will be instantly converted into a solid, at the same time a perceptible rise will take place in the temperature, which may be measured by immersing the bulb of a thermometer into the fluid.

Third Expt. Insert a thermometer into a saturated solution of sulphate of soda in water, to which add some pure alcohol. At the same moment a part of the salt will be crystallized, and the thermometer standing in the solution will give the measure of the heat which has been liberated.

The freezing points of some of the most important liquids are given below.

Water freezes at - - -	32°
Sea-water, of 1·027 specific gravity	27·41 Despretz. 26·82 Ermann. 23·00 Parrot.
Sulphuric acid, English, of 1·71 spec. grav. - - -	23·55 Berzelius.
Ditto, 1·84 spec. grav. -	11·66 Bellani.
Nitric acid, of 1·3 spec. grav. -	—2·20 Dalton.
Ditto, concentrated - -	—49·90 Parry.
Oil of turpentine, rectified -	—16·60.
Mercury - - -	—31 to —39·2 Ross. —40·9 Pouillet.

Hydrochloric acid, below	—40	Pouillet.
Sulphuretted carbonic acid	—49	Parry.
Sulphuric æther	—146	Mitchell.
Alcohol	—148 (?)	Thilorier.

§ 404.

Non-elastic fluids, and many solids in a state of fusion, when their temperature rises, acquire an increased repulsive force among their molecules, and assume the gaseous form. The peculiar undulatory movement of the liquid, caused by the ascent of the elastic fluid that is generated, is called *ebullition* or *boiling*, and the gas is termed a *vapour* or *steam*.

The *boiling point*, or the temperature at which ebullition commences, varies in different fluids, and, indeed, in the same fluid according to the pressure to which it is subjected. This pressure is principally caused by the atmospheric air, and by the aqueous vapour it contains; in a less degree it is owing also to the weight of the superincumbent strata of the fluid itself.

When the expansive force of steam exceeds this pressure, ebullition begins throughout the mass.

First Expt. Half fill with distilled water an extremely thin glass, which place in a sand bath, to avoid the risk of the glass flying: place the whole over a spirit lamp, immersing the bulb of a thermometer in the water; the thermometer will rise continually as more and more heat is imparted to the water. After some time a quantity of minute bubbles will be seen to attach themselves to the sides of the vessel, then gradually to rise to the surface of the water, and immediately vanish. These are in fact the gas contained in the water, principally indeed atmospheric air, which disengages itself from the heavier fluid as the temperature rises. (See § 57. *Second Expt.*) As the mercury rises towards 212°, fresh air-bubbles ascend, principally from the bottom of the glass to the upper strata, which, not being yet raised to a sufficient temperature, receive additional heat from these bubbles, until at length a perfect equality is established in the temperature of the fluid. Steam then begins to be generated, the formation of which may be known by a peculiar hissing sound, which just precedes the ebullition of the liquid. Lastly; when the entire mass of water has attained the requisite degree of heat, larger and larger bubbles of steam rise to the surface, where they burst and produce the undulatory movement known as ebullition. This last stage of the process is reached when the thermometer has risen to 212°, beyond which point it does not ascend, whatever the additional quantity of heat imparted, the continued application of which will diminish the water until it shall have completely disappeared. On this fact, the fixity of the boiling-point of the thermometer depends. (§ 366.)

The boiling points of some of the most important liquids, and that of certain solids, when in a state of fusion, are given below, the altitude of the barometer being 29·92196 inches.

	Fahr.	
Sulphurous acid boils at	14°	Bussy.
Muriatic æther	54	Gehler.
Nitric æther	69·8	Dumas.
Sulphuric æther	95	Munke.
Acetic æther	165·2	Dumas.
Alcohol, absolute	173·1	Gay Lussac.
Water, pure	212	
Vinegar, common	212	Mollerat.
Hydrochloric acid	220	Bineau.
Nitric acid, spec. gr. 1·42	249.4	Dalton.
Oil of turpentine	312·8	Dumas.
Sulphuric acid, common	550·4	Davy.
Linseed oil	600·8	Murray.
Mercury	680	Mitscherlich.
Camphor	219·2	Dumas.
Iodine	347	Dumas.
Phosphorus	554	Mitscherlich.
Sulphur	600	Mitscherlich.

With regard to the temperatures given above, as expressing the boiling points, these vary according to the purity of the liquid; thus, *ex. gr.*, solutions of salts boil at higher temperatures than water does; mixed fluids in like manner boil at different temperatures, according to the relative proportions of the substances composing the mixture. In many solutions of this class ebullition is attended with such violent jerks, that the thermometer can with difficulty be kept steady. Legrand observes that this inconvenience may be remedied by dropping a small piece of iron or zinc into the boiling liquid. Should this not abate the violence of the disturbance, drop in a piece of platina or glass.

One remarkable phenomenon connected with these fluids, and especially with water, is, that if placed in minute quantities on red-hot plates they do not boil, nor yet do they evaporate quickly, but, as the metal begins to cool, they assume a globular figure, and begin a rotatory and oscillating movement, during the continuance of which the process of evaporation is carried on much less rapidly than during ebullition. When the metal has cooled down to a still lower degree, the liquid boils with great violence, and is dispersed in every direction. These phenomena were first noticed in 1797 by Leidenfrost, and may be verified by the performance of the following experiment: —

Second Expt. Heat a platinum or silver spoon to a red-heat, by holding it over a spirit-lamp, and, through a tobacco-pipe or glass tube, conduct a drop of water on to the hot metal. The liquid will assume a globular form just like a drop of mercury, and will begin to revolve with great velocity, without boiling, during which process its volume will very slowly diminish. Remove the lamp, and the spoon will cool till in a little while it will fall to a temperature at which the drop of water it contains will either boil fiercely, or will fly apart with a small explosion. Dr. Böttger first remarked the stellated forms of the drop at the commencement of its gyrations, the size of the drop at the time being about half an inch. The excursions it performs resemble the curves described by the luminous speck in the kaleidophon (§ 214.), and show plainly that the molecules of the fluid are in a state of vibration.

Up to the present time these phenomena have not been quite satisfactorily accounted for; as far as regards the oscillatory movement they warrant the inference that the phenomena of heat are a consequence of the vibrations of the æther and of the constituent particles of bodies.

The more the pressure at the surface of any fluid is increased, the higher does the boiling point ascend; on the contrary, the less this pressure, the lower the point at which ebullition begins. It is owing to the atmospheric pressure that many liquids exist as such at ordinary temperatures; we may cite, as instances, alcohol, the various kinds of æther, &c.

Experiments 1 and 2. (§ 196.) may serve to confirm the above statement. The boiling of water or spirit of wine in the *water hammer* and in the *pulse glass*, on grasping either of these instruments with the hand, is owing entirely to the atmospheric pressure being removed from the surface of the fluid. The former of these two instruments has been described already in § 140.; the latter is merely a tube of glass, having a bore about 2 lines in diameter, but at right angles at each end, and expanded into two bulbs about 1½ inch in diameter. The instrument contains so much water or spirit of wine as suffices to fill the connecting tube and half of each of the bulbs, the space above the fluid being a vacuum; if one ball be grasped in the hand the liquid in the other will begin to boil violently.

The diminution in the atmospheric pressure is the occasion of water's boiling on high mountains at a temperature which is lower, just in proportion to the elevation of the mountain, or, what is the same thing, to the barometric altitude. (§ 202.) The following little table will exhibit at one view the boiling point of water at some of the principal elevations: —

Station.	Height in feet.	Heat of Barom.	Boiling Point.
Mont Blanc	15773	$17\frac{1}{20}$ in.	187·7°
Peak of Teneriffe	11936	$20\frac{87}{100}$	190
Quito	9485	$20\frac{78}{100}$	194
Hospice of St. Bernard	8173	$21\frac{1}{20}$	198

At such considerable elevations the heat of water boiled in open vessels is not sufficient to soften animal fibre, for which reason the inhabitants of these regions use Papin's Digester to prepare nutritious food. This apparatus consists of a close metal vessel, provided, for the sake of safety, with a valve to allow the escape of the superabundant steam. The accumulation of steam increases the pressure on the surface of the water, and thereby prevents its ebullition until a higher temperature has been arrived at than can be attained in the open air.

As the elevation of a place above the level of the sea may be found by knowing the amount of the atmospheric pressure (§ 202.), and as the point at which water boils will be lower the less this pressure, it follows that its amount may be determined from the height of the boiling point. Hence the truth of Wollaston's experiment for using the thermometer as an instrument for measuring altitudes. If the temperature at which water boils = t° Cent., the height of the barometer in metres may be found by the formula: —

$$^{*}\ \log.\ b = \frac{29{\cdot}945371\ .\ t}{800 + 3\,t} - 2{\cdot}2960374.$$

Lastly; from the above we see why, in determining the boiling point of a thermometer, reference is always had to the height of the barometer at that time, and consequently a correction is necessary if the mercury be above or below the standard height. (§ 371.) For every line above 28 Paris inches the scale must be shortened 0·0011 of its length from

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[*] NOTE. The formula in English standards may be found in Tredgold on the Steam Engine, p. 59. thus: —

the zero towards the boiling point, and for every line below 28 inches it must be similarly lengthened. *

The temperature of a liquid which is boiled in an open vessel does not rise, whatever the additional quantity of heat imparted to it. (This fact has been already noticed in the experiments described above.) As in the case of a melting body, so in the present instance, the excess of heat beyond what is requisite to produce ebullition is taken up by the steam. (§ 399.) The quantity of this latent heat varies according to the nature of the fluid.

Hence we see why it is practicable to boil water in paper, without the latter being burned; also, why a tin kettle is not melted when placed on burning coals, if it contain some water.

To ascertain how much caloric any fluid combines with itself in a latent state on being converted into steam, we must adopt a mode of procedure very similar to that by which we found the specific heat of gases. (§ 395.) A certain weight of the fluid we wish to examine must be converted into steam, in a vessel from which a tube passes in a spiral form, into a condensing vessel filled with cold water. The steam in its passage through the worm parts with all its latent heat, and the consequent elevation of the temperature of the water in the condenser, enables us to calculate the heat given out by the steam to the water. Thus, suppose that the condenser contained 15 lbs. of water at 54°, then the steam from one lb. of the fluid, in passing

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$$b=\left(\frac{t+100}{177}\right)^6;$$

or by logs. thus,

$$\log. b=6\left\{\log. (t+100)-2{\cdot}2479733\right\}.$$

Let $t^\circ=200^\circ$,

then

$$\begin{array}{r} \log. 300=2{\cdot}4771213 \\ -2{\cdot}2479733 \\ \hline {\cdot}2291480 \\ 6 \\ \hline 1{\cdot}374880 \\ \hline \log. b=23{\cdot}707 \text{ in.} \end{array}$$

Again; take $t^\circ=212^\circ$,

then

$$\begin{array}{r} \log. 312^\circ=2{\cdot}4941546 \\ -2{\cdot}2479733 \\ \hline {\cdot}2461813 \\ 6 \\ \hline 1{\cdot}4770878 \\ \hline b=29{\cdot}998 \text{ inches.} \end{array}$$

* Note. The correction for Fahrenheit's scale is 0·001 of the interval between the boiling and freezing points, for every tenth of an inch the barometer is above or below 29·8 English inches.

through the worm, would raise the temperature about $70\frac{3}{4}^\circ$, the water would therefore stand at $124\frac{3}{4}^\circ$. The water which had been converted into steam must therefore have given to these 15 lbs. of water in the condenser $15 \times 73\frac{3}{4} = 1061\frac{1}{4}^\circ$ of heat; whilst the steam reconverted to the liquid form has a temperature of $70\frac{3}{4}^\circ$, and must therefore have parted with $212^\circ - 124\frac{3}{4}^\circ = 87\frac{1}{4}^\circ$. Subtract the heat lost by the steam from that given out to the water in the condenser, and the difference $1061\frac{1}{4} - 87\frac{1}{4} = 974^\circ$ will be the latent heat of the steam.

The results obtained by the method described above, as determined by various philosophers, fluctuate between 954° and 1000°; the mean, as estimated by Despretz and Ure, is generally assumed to be correct, viz. that *steam at 212° contains 972° of latent heat.*— If then we take this as the value, it follows by the law of the equilibrium of temperature in similar bodies (§ 393.), that 1 lb. of steam at 212° would raise 5·4 times that weight of water from the freezing to the boiling point, for $972 = 5{\cdot}4 \times 180$, or it would raise 972 lbs. of water from 32° to 33°. Now since 1 lb. of ice requires 135° of heat to convert it into water of the temperature of 32° (§ 402. *Second Expt.*), it follows that water requires exactly $7\frac{1}{5}$ times as much heat to change it into steam at 212°.

As a general expression, let M represent the mass of water in the condenser, and T its temperature, m the mass of fluid to be converted into steam, and t its boiling point; lastly, t' the temperature obtained by the equalization of the temperature of the two masses of fluid; then the latent heat x of a unit of the steam may be found from the following equation: —

$$m\,(t - t') + m\,x = \mathrm{M}\,(t' - \mathrm{T}');$$

by transposition,

$$x = \frac{\mathrm{M}\,(t' - \mathrm{T}) - m\,(t - t')}{m}.$$

Dr. Brix, of Berlin, has recently carried on a series of very nice experiments, which have given for some fluids values differing considerably from the generally received values assigned them by Ure; the results arrived at by these two philosophers are exhibited below in a tabular form.

	Ure.	Brix.
Water - - - - -	967°	972°
Acetic acid (spec. gr. 1·007)	875	—
Ammonia (spec. gr. 0·978)	837	—
Nitric acid (spec. gr. 1·494)	534	—
Alcohol - - - - -	442 s. gr. 0.825	386 380 (s. gr. 0·798)
Sulphuric æther - -	302	162 (s. gr. 0·726)
Oil of turpentine - -	178	155 (s. gr. 0·867)

§ 405.

Liquids and some solids undergo an imperceptible change at their surfaces, by which they are converted into vapour. To this process the name of *vaporization* has been given; there is no fixed point at which it commences analogous to the boiling point or the point of fusion. Evaporation is carried on at various temperatures, and even under an extreme degree of cold. The counter-pressure of a similar gas, as we shall presently see, is the only force that suspends the continuance of the process.

First Expt. Fill a vessel with water, spirit of wine, æther, or any similar liquid, and place it in the open air; after some time the fluid will become sensibly less, and at length it will entirely disappear. The same will happen if camphor, carbonate of ammonia, or some such solid, be exposed to the action of the atmosphere. — Vapour has been observed to rise from mercury when at a temperature of only 14° Fahr., by holding a piece of gold-leaf just over the mercury, and the former has been covered completely with mercurial vapour.

But if substances which emit vapour from their surfaces, be enclosed in an air-tight glass, it has been found that they give out only such a portion as the enclosed air is capable of containing, and that the counter-pressure of the vapour already formed checks the production of any additional quantity at the surface of the evaporating body.

Evaporation may be accounted for thus: — Every body, —whatever the intensity of the cold to which it is exposed, contains a certain quantity of heat; the repulsive force subsisting between its component particles is neutralised or altogether destroyed by the predominant attraction in the interior of the body: but at the surface no such resistance is met with; and the particles so situated acquire such an expansive force, in consequence of the heat imparted to them, that they overcome the cohesive attraction; and separating themselves from the other particles, they pass off into gas.

We can conceive that for every substance whatever there exists some temperature so low, that the expansive force generated at the surface by the agency of heat is neutralized by the cohesion of the body, this will consequently be the *limit to its evaporation.*

From the above explanation it will be seen, why solid bodies, whose cohesive force greatly exceeds that of fluids, generally speaking, evaporate much less than they; and why under both forms of aggregation, bodies evaporate with greater or less readiness, according to their different degrees of cohesion. For the same reason it is obvious why, in the majority of solids, evaporation is altogether suspended, and of many the weight and form continue unchanged for centuries.

Many solids do, however, keep up an uninterrupted evaporation, as may be proved experimentally. A piece of ice, if exposed to the severest cold, will daily lose something in weight. The odour diffused by some substances demonstrates indisputably that they emit a vapour; thus, *ex. gr.*, many metals have a very peculiar smell. The vapours thus diffused from solids must be immeasurably finer than the rarest air, as many odorous substances (musk, for instance) (§ *5. 5.*), after the lapse of several years, do not lose such a portion of their weight, as is appreciable by the most delicate balance.

Vaporisation, which in its effects is precisely identical with boiling, is excited in fluids the more intensely the lower the temperature at which they boil. It is, however, accelerated still more, by elevating the temperature of the fluid, and by increasing the extent of its surface. The rate of evaporation is also raised by the dryness and rarity of the air, as also by frequently changing it by means of currents.

The quantity of heat which vapours combine in a latent form in the course of their formation, is exactly equal to that which the fluid absorbs during its conversion into steam by boiling. The fluid derives a portion of this heat from itself during the process of evaporation, and part it draws from the bodies with which it stands in contact; the temperature of both will therefore be lowered. A degree of cold is accordingly produced, resembling that which obtains when salts are dissolved (§ 402.), which will be greater or less as the evaporation is more or less rapid. An extreme degree of cold may, indeed, be generated by this means.

The following experiments will confirm the truth of what has been just advanced: —

Second Expt. Wrap some muslin, cotton, or wool, round the bulb of a thermometer, and plunge it in spirit of wine, sulphuric æther, or sulphuretted carbonic acid; as the envelope dries by the evaporation of the liquid with which it is saturated, the temperature of the thermometer falls. The mercury will descend still more rapidly if the thermometer be moved quickly to and fro through the air, or if a current of air be directed on the bulb by blowing a pair of bellows. — If sulphuric æther be used, the thermometer will fall even in summer below the freezing point; and with sulphuretted carbonic acid it soon descends from 67° to 0°.

These effects are exceeded by the still more rapid evaporation of liquid sulphurous acid, by means of which Bussy has succeeded in congealing the mercury in the bulb of a thermometer in the open air. If this acid be carefully dropped on water, the latter will instantly be covered with a thin film of ice.

Third Expt. A few drops of spirits of wine, or sulphuric æther, let fall on the back of the hand, evaporate quickly if the hand be moved backwards and forwards, and a sensation of great cold will be produced on that spot.

The sensation of cold experienced on coming out of a bath, or on being wet with rain, is owing to this combination of the latent heat with the fluid as it evaporates. By the same means ice is made artificially in the East Indies; so also water is cooled in Spain, in porous earthen vessels, called alcarrazas. Wine, too, is cooled on board ship by wrapping wet cloths round the bottles, and hanging them up so as to be exposed to a current of air. — The cooling of cannon by wiping them out with the sponge is mainly owing to the rapid evaporation of the water caused by the heated metal. — The evaporation by perspiring enabled Fordyce, Banks, Solander, and Blagden to continue for 8 minutes in a chamber heated to 257°. In the Austrian salt-mines the men work at a temperature of 240° in those chambers where the salt is dried; and in some furnaces and blast-houses the workmen are exposed to still greater heat without their bodies being heated much beyond the normal temperature.

Even in the height of summer an intense cold may be generated if we accelerate the evaporation by rarefying the air, and especially if we make some arrangement by which the vapour that is thrown off may be absorbed by some other body. This may be verified by the following experiment: —

Fourth Expt. — *Leslie's Experiment.* — *Water frozen by evaporation.* Water at 68° by evaporation must absorb 36 + 972 + 135 = 1143° of heat.

Fig. 112.

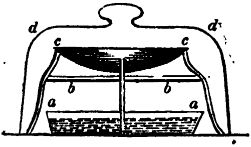


Fig. 112. represents the requisite apparatus. *a a* is a glass or porcelain vessel, about 5 or 6 inches in diameter, over which a little tripod stands, bearing a thin metal cup, *c c*, of about the same size as *a a*; the distance between these two should not exceed 2 or 3 inches. Fill the lower vessel with concentrated sulphuric acid, and the upper one with the water you propose to freeze; the aqueous vapour of the water will be absorbed by the acid. The whole apparatus is to be placed under a bell-glass on the plate of an air-pump, and the air is to be rapidly exhausted. When the barometer gauge stands at 2 lines, crystals of ice will shoot across the surface of the water; and if the external air be excluded from the receiver, the whole mass will soon be converted into ice. The water is elevated on a tripod, that the acid may not fall into it should the apparatus be shaken. — The successful performance of this experiment is considered as a pretty good test of the excellence of an air-pump.

On removing the bell-glass, after all the water has been frozen, it will be found that the sulphuric acid, though so near to the cup containing the ice, is considerably heated; whence it appears that the heat which the aqueous vapour abstracted from the water during its formation, and the loss of which caused the latter to freeze, has passed as free caloric to the acid which absorbed the vapour and reconverted it into the liquid form. — If the ice thus formed be left in the vacuum under the receiver, the continued evaporation will lessen its dimensions until it finally disappears.

Fifth Expt. — *Configliarchi's Experiment.* — *Mercury frozen by the evaporation of sulphuric æther.* — Since sulphuric æther in its conversion into vapour (§ 404.) absorbs 302° of latent heat, and liquid mercury contains 157° of the same, if both fluids have the temperature of 68°, then 302 + 157 + 36 = 495° of heat will become latent before the mercury is frozen.

Fig. 113.

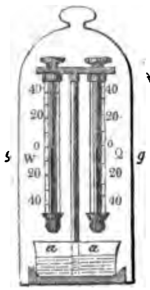
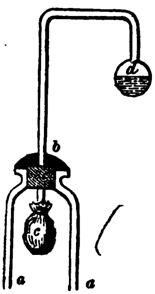


Fig. 113. represents the arrangement for the performance of this experiment. Q is a mercurial, and W a spirit of wine thermometer, with corresponding scales. Both are fixed side by side, and beneath them is a glass vessel, *a a*, whose bottom is about 3 inches below the balls of the thermometers, which should be surrounded with cotton saturated in highly rectified sulphuric æther. Pour sulphuric acid into the glass trough, to the depth of about half an inch, place the apparatus on the plate of an air-pump, covering it with as small a receiver as possible, *g g*. When the air under the bell-glass begins to be rarefied, the evaporation of the sulphuric æther in contact with the bulbs of the thermometers goes on at an increased rate, and the fumes of æther thus generated are absorbed by the sulphuric acid. During this process a rapid fall of the thermoscopic substances is observable; and when the mercurial thermometer stands at −40°, and the spirit of wine thermometer at about −32°, the metal suddenly contracts; and if the bulb be not much below the above named point, the mercury descends entirely into the bulb, and solidification commences, at the moment when the barometer gauge has fallen to about 4 lines. — If exhaustion be carried on, the spirit of wine thermometer may be made to descend as low as −49°. — Besides the mercurial thermometer suspend also, under the receiver, a short thermometer tube, whose bulb is only partly filled with mercury; surround the bulb with cotton or some such substance saturated with sulphuric æther, and you will find, as the air is exhausted, and the æther passes off in vapour, that the metal will be solidified.

This experiment affords us an opportunity of observing the formation of hoar-frost, of which more will be said in the next section. Remove the envelope from the ball of the thermometer, hold up the instrument towards the light, and a fine mist will be seen to rise in the air. In a little time a thin white deposit will be formed on the bulb, which becoming thicker and thicker at length crystallizes. This is actually hoar-frost, which is formed by the congealing of the aqueous vapour of the atmosphere surrounding the bulb of the thermometer on which it deposits itself, and where it remains until the mercury rises to 32°, when it suddenly vanishes from the surface it covered.

Sixth Expt. The cryophorus is a very simple instrument, invented by Dr. Wollaston, for freezing water by its own evaporation. — It consists of a glass tube, from 12 to 24 inches in length, and about one third of an inch in width; its two ends are bent one way at right angles to the main part of the tube, and are widened at the extremities into bulbs of 1 or 2 inches in diameter. One of these balls is half filled with water, the remaining space is a vacuum. Plunge the empty ball into a freezing mixture (§ 402.), and the water in the other will be turned into ice. — The bulb in the freezing mixture is filled with aqueous vapour, which is rapidly condensed, and as there is no air in the tube, more vapour is rapidly formed, and so much heat is abstracted from the water that it freezes. — Marcet substituted sulphuric æther for the freezing mixture, having first wrapped some cotton around the bulb, which he sprinkled with æther, and then hastened evaporation by blowing on it with a pair of bellows. The experiment may be performed better and more quickly if the bulb which is to be cooled be placed in a receiver from which the air is exhausted by pumping. *Fig.* 114. represents a simple arrangement adapted for this purpose. *a a* is a receiver, open at top, *b*, where the tube of the cryophorus is so fitted that its empty bulb, *c*, previously surrounded with cotton well saturated with sulphuric æther, shall be in about the middle of the receiver, whilst the other bulb, containing the water, is outside the glass.

Fig. 114.



§ 406.

When steam or vapour comes in contact with a body cooler than itself, the latter abstracts from it such a portion of its caloric that it returns again to its original form of aggregation. During this process of *condensation*, as it is called, all that heat is liberated which had caused the body to assume the gaseous form.

Expt. Hold a plate of glass or metal over a vessel containing boiling water, the vapour which rises is condensed into drops upon the cold surface of the plate, which becomes heated by the steam.

The experiment described in § 404., by which we estimated the latent heat of steam, depends on the liberation of this heat by the condensation of the steam.

The conversion of liquids or solids into vapour, and their reconversion into their former state of aggregation, is made use of both for chemical and technical purposes. When liquids are changed into vapour by heat, and are then condensed again into liquids, they are said to be *distilled.* The same process applied to solids is called *sublimation;* and the vapour which, by cold, is restored to the solid form, is called a *sublimate.* Both operations are of service, sometimes for combining different substances, sometimes for separating one from others with which it is united. Fuller details belong rather to a treatise on chemistry. (Compare § 84.)

Many natural phenomena, a complete account of which it is the province of Meteorology to give, are consequences of condensation by cold. Such are mists, clouds, rain, snow, hail, dew, and hoar-frost. — The moisture and the glazed frost, visible on windows, are also merely the aqueous particles of the air in a condensed state.

VI. PROPERTIES WHICH DISTINGUISH STEAM AND VAPOUR FROM THE PERMANENT GASES.

§ 407.

Steam and *Vapour* are strictly homogeneous, and differ from each other, as has been said already, only in the mode of their production. They are both generated by the action of heat expanding the constituent atoms of solid and liquid bodies, and causing them to repel each other. This change of form is unaccompanied by any alteration in the chemical composition of the substances. Gaseous fluids differ one among another both physically and chemically, according to the body from which they are formed by its combination with heat. Thus we speak of aqueous vapour or steam, of mercurial, sulphurous, and other vapours. The most important of all, on every account, is steam. Its properties only will therefore be treated of at length through the remainder of this portion of the work.

It has been observed incidentally (§ 179.) that these gaseous fluids resemble the permanent gases in many respects, but that in others they differ widely from them. The principal point of distinction between them is this, that *steam, by a lowering of its temperature, or by increasing the pressure on it, may be reduced to its original form of aggregation, but that permanent gases cannot be thus acted on.*

§ 408.

So long as the temperature continues unchanged, only a certain quantity of steam can be generated in a close vessel; as soon as it becomes full of vapour, no more is generated by the liquid it contains, provided that the same temperature is maintained. Under such circumstances the space would be said to be saturated with steam, which is called either *saturated* steam, or steam *of maximum density.*

When applied to mechanical purposes, steam is generally used at its maximum density, for which reason there ought always to be in boilers and digesters a sufficient quantity of water completely to saturate the space they contain. The aqueous vapour held in the atmosphere is very rarely indeed in a saturated condition, being found so only in rain and dense fogs. Generally speaking, we may assume, if a vessel contain a liquid which is giving off steam, that that vessel is filled with steam at a maximum density.

§ 409.

The *density* of steam in this condition varies with its temperature, for, if that be raised, more of the liquid is converted into steam; the quantity of the latter, and also its density, are consequently increased. If the temperature fall, a portion of the steam resumes the liquid form; the quantity of steam and its density are diminished.

The relative density of steam, or its specific gravity, has been investigated experimentally, and it has been ascertained that the ratio of the density of saturated steam to the density of atmospheric air is a constant quantity, provided they are both under equal pressures and at equal temperatures. Gay Lussac has estimated the density of steam under these conditions, to be invariably 0·6235, or five-eighths of the density of the atmosphere. Comparing this with the density of water, it follows that that of steam at 212° is about $\frac{1}{1700}$ (or, more exactly, $\frac{1}{1683}$) of the density of water; that is to say, steam at this temperature would fill a space 1700 times greater than that of the water which produces it; 1 cubic foot of water (at its maximum density, § 376.) would be converted into 1700 cubic feet of steam at 212°.

The weights of bodies whose volumes are equal are as their densities, whence from the known or required density of the steam we may calculate its weight. Let x be the weight of 1 cubic foot of atmospheric air at 32°, the barometer having a mean altitude of 80 inches, then, by § 377., for t° Fahr., its weight is

$$\frac{x}{1 + 0{\cdot}002037\ t};$$

whence the weight of steam is

$$\frac{5}{8} \cdot \frac{x}{1 + 0{\cdot}0002037\, t} = \frac{0{\cdot}6235\ x}{1 + 0{\cdot}002037\, t}.$$

Now 1 cubic foot of air at 32° weighs 0·081lb., the barometer standing at 29·92 inches; if, therefore, the water be made to boil at 212°, 1 cubic foot of the steam will weigh

$$\frac{0{\cdot}6235 \times 0{\cdot}081}{1 + 0{\cdot}002037 \times 180} = 0{\cdot}0369\text{lb.}$$

§ 410.

Steam, like gas, has a tendency to spread itself in all directions; the expansive force which it displays, commonly called its *tension*, depends, not merely on its density, but it also increases when the temperature is raised.

At equal temperatures the tension of steam is directly as its density; that is to say, any given quantity of steam will exert $\frac{1}{2}$, $\frac{1}{3}$rd, $\frac{1}{4}$th, $\frac{1}{n}$th, as great an expansive force with twice, three times, four times, n times the volume, it being understood that the temperature in each case remains the same.

If the density be uniform, then the tension increases with the elevation of the temperature; the expansion of steam by heat obeys the same law and requires the same force as the permanent gases, viz. $\frac{11}{5400}$, or 0·002037 of its volume for every degree of heat from 32° to 212°.

If, therefore, E be the expansive force or tension at 32°, and E′ that at t°, then

$$\begin{aligned} E' &= E\left(1 + \frac{11}{5400}\,t\right), \\ &= E\,(1 + 0{\cdot}002037\,t). \end{aligned}$$

But if the density of the steam increase as well as its temperature, which does really happen when there is a large quantity of fluid giving off steam in a closed vessel, then the tension of the steam will be increased, both by the expansive force of the heat, and also by its own progressive density. In this case it is obvious, that its tension will increase faster than the temperature rises. Steam of maximum density is always of the same temperature with the water from which it is generated, if its temperature be not brought down by the operation of any external cause, thus, *ex. gr.*, a thermometer immersed in the fluid would stand at the same degree as another thermometer in the steam given off. Hence, by knowing the temperature of the water, the tension of the steam can be calculated. It must be remembered though, that the law by which the tension of steam at maximum density rises with the temperature is not at present exactly known, all the formulæ yet constructed for expressing it coinciding with experiment only within certain limits.

§ 411.

Steam, formed by the ebullition of a fluid in the open air, must (by § 404.) have a tension sufficient to overcome the atmospheric pressure on its surface. If this pressure be greater than usual, the steam must acquire a higher elastic force before the liquid will begin to boil; but by the preceding section this greater elasticity is gained by an increase in the temperature; hence, if the pressure be increased, the boiling point is elevated.

That which is brought about in the open air by an increased atmospheric pressure, is effected in close vessels by the steam already generated; and as, by the preceding section, it was shown that the density and the tension were increased by a rise in the temperature, so we now find that the boiling point will be proportionably elevated. We have thus the power of controlling the heat at which water shall boil, and consequently are enabled at pleasure to increase or diminish the expansive force of the steam that is generated.

> *Expt.* Fill a Florence flask about half full with water or weak spirit, and make the fluid boil briskly for some minutes by holding it over a spirit lamp; then cork it closely. Above the surface of the water there will be nothing but steam, and ebullition will cease when the lamp is removed. Invert the flask so that its mouth may be downwards, and pour cold water on the surface now placed uppermost, the expansive force of the steam will be thereby diminished, as also will its pressure on the surface of the water, which will begin to boil again. Pour a little hot water on the flask, the tension of the steam will be restored, and its pressure on the water being increased, ebullition will once more cease.

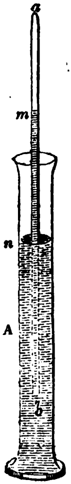
§ 412

There are two ways of estimating practically the *pressure* steam exerts in consequence of the increased expansive force it acquires according to its density and temperature. By the first of these modes it is calculated as the atmospheric pressure is, by observing the height of the column of mercury it is able to support; this pressure is then compared with that of the atmosphere. (§ 193.) According to the second method, it is expressed by the weight the steam is able to raise, when it is made to act upon a valve of known size, on which the weights are placed.

The importance, both for scientific and practical purposes, of our being able to estimate the amount of this pressure at different temperatures, has induced many of the greatest philosophers of our times to investigate the subject; but a brief account of the various courses they have adopted to arrive at correct results, can be given in the present treatise; for further details the reader must of necessity be referred to the original works.

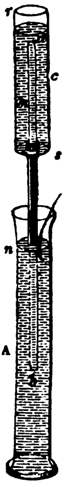
Dalton made use of the Torricellian tube to estimate the expansive force of steam, at temperatures lower than that of boiling water. He nearly filled a common barometer tube (*a b*, *fig.* 115.) with mercury, the small space remaining unoccupied by the metal he filled with the fluid, whose vapour he wished to investigate, then placing the finger on the open end of the tube he inverted it, as in the Torricellian experiment, and plunged the lower end in a vessel A of mercury. The mercury in the tube sinks, for reasons already explained, and the lighter fluid rises to the upper part of the tube, which, being a vacuum, is immediately filled with the fluid in the form of vapour, at a maximum density. The height of the mercury in this tube was then compared with that of the column in the barometer, and in consequence of the pressure of the vapour, it was, of course, lower than the latter; the difference between these two columns is the measure of the expansive force of the steam at that particular temperature. For instance, suppose the height of the barometer to be 30 inches, and that of the mercury in the other tube to be only 29 inches, then the tension of the steam would hold in equilibrium a mercurial column 1 inch in height, to which, therefore, we should say it was equal. To determine the expansive force at different temperatures, it will be convenient to sur-

Fig. 115.



round the upper part of the Torricellian tube with a wider glass tube (C, *fig.* 116.), closed at bottom with a cork, through which the former passes; place a thermometer within the larger tube, and fill it with water at different temperatures. If the water be hotter than the air, the mercury will sink lower than before; if it be colder, the mercury will rise, and the expansive force of the steam may be calculated for each of the temperatures, from the differences in the height of the mercury in the tube and in the barometer.

Fig. 116.



The expansive force of the vapours may be easily determined by means of the air pump, and the results thus obtained very nearly accord with those found by Dalton. The following will be the mode of conducting the experiment.

Expt. Place a flask, containing a thermometer, about half full of warm water, under the receiver of an air pump, and exhaust the air until the water begins to boil. The height of the barometer gauge (§ 200.) at that moment gives the tension of steam of maximum density at the particular temperature indicated by the thermometer in the flask. Any other fluid can, of course, be substituted for water; and the experiment can be repeated with the fluid at different temperatures.

The manometers (*figs.* 136 and 137. Vol. I., described in § 200.) are used for measuring the expansive force of steam; in the former the pressure is shown immediately, by the height of the mercurial column in the manometer tube; in the latter, which is used for steam of high expansive powers, the pressure is determined by Mariotte's law, § 197., and is shown on the scale in atmospheres.

If the expansive force of steam be determined by the weight it is able to raise, we use an apparatus closely resembling the *safety valve* of a steam engine in its construction, of which a representation is given below in *fig.* 177., V is a valve shaped like a truncated cone, connected with a single-armed lever, *c a b*, by a moveable metal rod, *a v*; on the longer arm, *a b*, of the lever a moveable weight, *w*, is suspended, by means of which the valve is pressed down into its place. When the steam within the boiler has acquired an expansive force which exceeds the pressure exerted by the lever on the upper side of the valve, it raises the valve and escapes; the pressure it has exerted is indicated by the weight hung on the end of the lever. Thus, suppose the

Fig. 117 *b.*

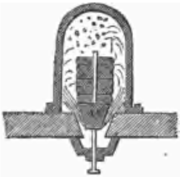
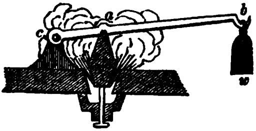


Fig. 117 *a.*



under tube of the valve to be 1 square inch, and that the weight *w* presses it down with a force of 15lb., then the pressure of the steam must be at least 30lb. to the square inch before it will raise the valve, which is pressed down by a weight of 15lb., and by the atmospheric pressure, which is also about 15lbs. per square inch.

The law has not yet been discovered by theory for the increase in the expansive force of steam at every temperature; in default of this, we are compelled to use empirical formulæ, deduced from the results afforded by the best conducted experiments. Of these formulæ there are very few that are applicable under all circumstances; for such as are true for high temperatures, fail when used for low ones, and vice versâ.

In note * to § 404. we have already given, from "Tredgold on the Steam Engine," a formula by which to find the force of steam from water, in inches of mercury, the temperature being given.

$$\log. b = 6 \{ \log. (t + 100) - 2{\cdot}2479733 \}.$$

In the following table the reader is presented, at one view, with the results of experiments conducted by Watt, Dalton, Ure, and Southern, compared with the above formula:—

TABLE XII.

Temperature of Steam.	Force in Inches of Mercury, according to the Observations of				Force in Inches, &c., by Formula.
	Watt.	Dalton.	Ure.	Southern.	
24°	—	—	0·170	—	0·118
32	—	0·2	0·200	0.16	0·172
36	—	*0·29	—	—	0·201
40	—	—	0·250	—	0·245
42	—	—	—	0·23	0·266
43¼	—	0·297	—	—	0·281
50	—	—	0·360	—	0·37
52	—	—	—	0·35	0·401
54½	—	0·435	—	—	0·442
55	0·15	—	0·416	—	0·45
60	—	—	0·516	—	0·55
62	—	—	—	0·52	0·587
64	—	*0·75	—	—	0·663
65¾	—	0·63	—	—	0·675
70	—	—	0·726	—	0·78
72	—	—	—	0·73	0·842
77	—	0·91	—	—	1·000
80	—	—	1·010	—	1·106
82	—	—	—	1·02	1·182
88¼	—	1·29	—	—	1·447
90	—	—	1·360	—	1·53
92	—	—	—	1·42	1·629
96	—	*1·95	—	—	1·84
99½	—	1·82	—	—	2·05
100	—	—	1·860	—	2·08
102	—	—	—	1·96	2·21
110	—	—	2·456	—	2·79
110¾	—	2·54	—	—	2·85
112	—	—	—	2·66	2·95
118	2·68	—	—	—	3·59
120	—	—	3·300	—	3·68
122	—	3·5	—	3·58	3·89
130	—	—	4·366	—	4·81
132	—	*5·07	—	4·71	5·07
133¼	—	4·76	—	—	5·24
140	—	—	5·770	—	6·21
142	—	—	—	6·10	6·53
144½	—	6·45	—	—	6·95
150	—	—	7·53	—	7·94
152	—	—	—	7·90	8·33

TABLE XII.—*continued.*

Temperature of Steam.	Force in Inches of Mercury, according to the Observations of				Force in Inches, &c., by Formula.
	Watt.	Dalton.	Ure.	Southern.	
155¾	—	8·55	—	—	9·10
160	—	—	9·600	—	10·05
162	—	—	—	10·05	10·52
167	—	11·25	—	—	11·7
170	—	—	12·050	—	12·6
172	—	—	—	12·72	13·17
173	—	*13·18	—	—	13·46
178¼	—	14·6	—	—	15·1
180	14·73	—	15·160	—	15·67
182	—	—	—	16·01	16·35
189½	—	18·8	—	—	19·15
190	—	—	19·000	—	19·35
200	—	—	23·600	—	23·71
200¾	—	24·0	—	—	24·07
210	—	—	28·88	—	28·86
212	—	30·0	30·00	30·00	30·00
220	—	*34·20	35·54	—	34·92
225	37·	—	39·11	—	38·32
230	—	—	43·10	—	42·00
240	49·	—	51·70	—	50·24
250	—	—	61·90	—	59·79
250·3	—	—	—	60·00	60·00
260	—	—	72·30	—	70·8
261	68·	—	—	—	72·00
270	—	—	86·30	—	82·45
272	—	88·9	—	—	86·2
272·5	82·	—	—	—	86·89
280	—	—	101·90	—	97·92
290	—	—	120·15	—	114·40
293·4	—	—	—	120·00	120·50
295	—	—	129·00	—	123·50
300	—	—	139·70	—	133·20
310	—	—	161·3	—	154·5
312	—	—	167·0 165·5	—	159·0
340	—	*231·0	—	—	236·00
343·6	—	—	—	240·00	247·80

TABLE XIII.

Temperature of Steam.	Force in Atmospheres at 29·922 Inches, and 32° Fahr.	Force in Inches of Mercury.	Temperature of Steam.	Force in Atmospheres at 22·922 Inches, and 32° Fahr.
212°	1	29·922	356°	11
233·9	1½	44·930	374	12
250·5	2	59·842	380·7	13
263·8	2½	74·604	386·9	14
275·2	3	89·765	392·8	15
285	3½	104·725	398·5	16
293·7	4	119·687	403·8	17
300·3	4½	134·647	408·9	18
307·5	5	149·609	413·7	19
314·2	5½	164·569	418·5	20
320·3	6	178·631	422·9	21
326·25	6½	193·591	427·2	22
331·7	7	209·453	431·4	23
336·8	7½	224·413	435·5	24
341·7	8	239·374	439·3	25
350·7	9	269·296	666·5	40
358·8	10	299·218	690·7	50

EXPLANATION OF TABLES XII. AND XIII.

From inspection of the above table, it will be seen at once that the force of the steam, as found by Mr. Watt, is less than it ought to be, especially at low temperatures. The numbers marked with an asterisk, in the column headed Dalton, are taken from a table which that gentleman formed from what he considered the most correct experiments on the subject. With regard to Dr. Ure's table, Mr. Tredgold observes, that the later enquiries of Mr. Dalton justify the numbers being higher, at or about 150°, than Dr. Ure's. Mr. Southern's experiments were conducted with such care, that Mr. Tredgold says they seemed to him entitled to great confidence, and hence he made the results the principal data for his formula.

Table XIII. gives the force of steam from 1 to 10 atmospheres, with especial reference to the construction of steam engines, as determined by the recent experiments of a commission appointed by the "Academie des Sciences" of Paris, the members of it being Arago, Dulong, Girard, and Prony.

The force may be found, by the following formula, from 5 atmospheres to 50: —

$$t = \frac{\sqrt[5]{e} - 1}{0{\cdot}7153};$$

e being the elastic force in atmospheres, and t the temperature + 100° Cent., the interval from 100 being assumed as unity. The degrees of the thermometer are expressed in the table above according to Fahrenheit's scale, and the column of mercury has also been reduced to English inches.

§ 413.

It will easily be inferred, from the remarks already made, in what points vapours resemble the permanent gases, and in what they differ from them.

We propose now to consider what is *the effect of the pressure* consequent upon either enlarging or contracting the space which contains the vapour.

A mass of air suffers no change in its form of aggregation, whatever the expansion or contraction of the space it occupies: in the former case its density, and consequently its expansive force, are diminished; in the latter they are increased; and this increase and decrease are inversely as the change in volume.

A mass of steam in a close vessel resembles a permanent gas thus far, that if its volume be increased, or the pressure on it diminished, it becomes more rare; but the similarity holds good with regard to its condensation consequent upon the diminution of its volume, or the increase of pressure, only to the point at which steam attains its maximum density for the particular temperature; when this point has been reached, the least additional increase of pressure, or contraction of space, causes a partial conversion of the vapour into a liquid.

Depress the Torricellian tube in Dalton's experiment (which has been described in the preceding section) lower in the vessel of mercury, and the space above the mercurial column that is filled with the vapour of that fluid which is being experimented on will be diminished; and as this vapour is at a maximum density, so much of it will be reduced to the liquid form as equals the diminution of the space that contains it. The amount of the reduction will be shown by the increase in the length of the column of fluid supported by the column of mercury, the height of the latter remaining unchanged. Now, according to Mariotte's experiment (§ 197.), had the space above the mercury been occupied by air, the column of mercury would have become *shorter* when the tube was depressed in the cistern. Continue to depress the tube until the mercury rises almost to the closed end, and the whole of the vapour will be changed into liquid.

The following illustration may perhaps render the preceding observation more easily comprehended. Suppose a quantity of vapour at 212° to expand and occupy so large a space that its tension is reduced one half, *i. e.* till it equals only half an atmosphere; then, as the pressure diminishes, and the volume increases, rarefaction goes on precisely as in the case of atmospheric air. Next, if it be subjected to the converse operation, we shall find that it may be compressed till its expansive force again equals 1 atmosphere, that being the maximum for steam at 212°; but if the process be continued beyond that point, *ex. gr.*, till its volume is reduced one half, then one half of the vapour will resume the liquid form, but the other half will still be vapour, with a maximum expansive force of 1 atmosphere. Thus a permanent and progressive pressure might convert the whole mass of steam into liquid.

§ 414.

Gases and vapours are not affected by *heat* in precisely the same manner.

Every gas enclosed in a space acquires an increased expansive force (§ 377, 378.), corresponding with the index of its expansion if its temperature be elevated; and conversely, the expansive force is proportionally diminished if the temperature of the gas be lowered. The limits have not yet been ascertained to the increase or decrease of this force.

Now, the elevation of the temperature of a mass of vapour enclosed in a space is affected precisely as a mass of any elastic fluid would be; that is to say, its tension increases; but if its temperature be lowered, its expansive force will gradually become less, whilst, at the same time, a corresponding portion will lose the form of vapour and be converted into a liquid.

Suppose a certain space to be filled with steam at 212°, then at a maximum density its expansive force will equal 30 inches, or 1 atmosphere. Cool this mass to 180°, and its maximum tension will be lowered to about half an atmosphere; and so much of the steam will have been converted into water, that the remaining portion filling the space unoccupied by the water will have a tension of 0·5 of an atmosphere. If the temperature be lowered still more, the remaining portions of steam will be successively condensed till its elastic force will equal only about 0·137 of an inch, or 0·005 of an atmosphere. Had this quantity of steam been raised to a higher temperature, instead of being cooled, suppose, for instance, from 212° to 250°, its tension (by § 409.) would have been elevated in the proportion of

$$1+(180\times 0{\cdot}002037) : 1+(218\times 0{\cdot}002037) = 1366 : 1444 = 1 : 1{\cdot}06.$$

Hence, if there had been an increase of 38° in its temperature, its expansive force would have increased only 0·06 of an atmosphere; whereas, had the steam been at its maximum density at 252°, the expansive force would have equalled 2 atmospheres. This steam might therefore be cooled without any condensation, but obviously not lower than 212°, when its maximum density would be attained.

§ 415.

Dalton's experiments have led to the discovery of this remarkable fact, that the same quantity of steam may be raised from any liquid, in a space filled with any kind of gas whatever, as in a vacuum; the only difference is, that in the latter, the quantity of vapour requisite to saturate the space is generated almost instantaneously, whereas, when the space is charged with a gas, the process goes on the more slowly the nearer the steam is to its maximum density. The air thus combined with vapour possesses an expansive force, equal to the sum of the forces of the gas itself, and of the vapour at the particular temperature.

§ 416.

Steam or vapour generated in the open air, is emitted from the fluid in a state of saturation, answering to the particular temperature, and is consequently at a maximum density near the surface of the liquid: since, however, under these circumstances, it is free to expand in all directions its density diminishes at a small distance from the boiling surface. If there come in contact with the surface of the liquid, a stratum of air so cold that the aqueous vapour, on entering it, attains its maximum density, all further evaporation ceases. A further depression of the temperature causes the aqueous vapour in the air to be converted into water, and so produces the hydro-meteors mentioned in § 406.

Hence it appears that the quantity of vapour in the atmosphere at any particular time depends principally on its temperature, and, as this is not uniform in all places, and even varies from time to time in the same place, it is obvious that different portions of the atmosphere will be unequally charged with vapour, and that the quantity at the same place will vary at different times.

HYGROMETRY.

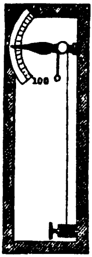
§ 417.

It is often a matter of importance, both for physical and meteorological purposes, to be able to measure the quantity of aqueous vapour with which the atmosphere may be charged. That part of science which treats of this subject is termed *Hygrometry*, and the instruments used to measure the moisture of the air, *i. e.* which are intended to show the quantity and condition of the vapour it contains, are called *Hygrometers*; if they merely indicate the presence of aqueous vapour, without measuring its amount, they are called *Hygroscopes*.

The sorts of apparatus used for these purposes differ very considerably, both in their construction and in the principle on which they act; few, however, answer perfectly well.

They may be arranged in three classes: in the first, we may reckon all those in which some substance is made use of, that absorbs the aqueous vapour with which the air is charged, according to its various degrees of moisture: this substance, thereby, expands or contracts, undergoing certain changes in its dimensions, the extent of which furnishes us with an instrument for measuring the condition of the air as regards moisture. Bodies which possess, in a high degree, the property of absorbing the moisture from the atmosphere, and which readily part with it again when the air becomes dry, or recedes from its saturated condition, are termed *hygroscopic substances*: they are mostly of animal or vegetable origin; we may instance hair, fish-bone, ivory, animal membranes, and intestines, the beard of wild oats, wood, &c. The defect common to all these is, that the moisture of the air so affects them, when they have been for some time exposed to its influence, as to render them less susceptible, and so prevent their being comparable one with another. Besides, both this class and that of which we shall next speak, express rather the degree in which the atmosphere approximates to a condition of saturation than the exact amount of moisture it contains. In even the best of these hygroscopes, therefore, the same degree of the scale which represents a certain approach to a state of saturation, would represent the existence of various quantities of vapour in the atmosphere, according as its temperature is high or low. These indications are, however, important, as they show what is the probability that there will or will not be rain: they also lead us to believe that the readiness with which other substances in the air become moist, depends rather on the degree in which the atmosphere approximates to a saturated condition, than on the quantity of vapour it contains. The best known and most accurate instrument of this sort is *Saussure's hair hygrometer*.

Fig. 118.



This hygroscope is constructed thus: A human hair, about 8 or 12 inches long, is freed from all animal grease by boiling it in a weak caustic ley; one end of it is then made fast to a hook, and the other is passed over a pulley fixed in a frame, and is strained tight by means of a small weight. The contraction and expansion of the hair communicates motion to an index attached to the axis of the pulley. The sketch of such an instrument given in *fig.* 118. renders further description superfluous. The two normal points of the scale are, that at which the index stands in a perfectly dry atmosphere, and that at which it stands in an atmosphere saturated with humidity. The former point is marked zero, and the latter is generally marked 100, the intervening space being divided into that number of degrees. The zero is found by placing the apparatus under a bell-glass, in which there is a considerable quantity of chloride of calcium, or of concentrated sulphuric acid, by which all the aqueous vapour is absorbed. The point of greatest humidity is determined by placing the instrument under a bell-glass, the inner surface of which has been well sprinkled with water, or which is stood over a vessel of water, so that the air may become thoroughly impregnated with moisture. The degrees shown by this hygroscope, as we have already remarked, are not proportional to the mass of vapour held in the air; that is to say, when the index stands at 80°, or 50°, or 25°, we are not warranted in inferring that the atmosphere contains $\frac{4}{5}$. $\frac{1}{2}$, or $\frac{1}{4}$ as much vapour as when it points to 100°; all that can be deduced is, that at 50° the air is farther from being saturated with moisture than at 80°, or at 25° than at 50°. Gay Lussac determined, experimentally, the elastic force of the aqueous vapour held in the atmosphere at a temperature of + 10 Cent. = 50° Fahr., answering to the degrees of the hygroscope, and thence compiled a table, which Biot, by interpolating, completed.

In the second sort of hygroscopes such substances are used as show by the quantity of moisture they absorb from the atmosphere and give back to it, its degree of humidity; they differ, therefore, from the kind already described, in which the contraction and expansion of the hygroscopic substance itself served as our guide. The principal substances used are of inorganic origin, chiefly salts, such as chloride of ammonia, caustic potash, chloride of sodium, &c., sulphuric acid, and some sorts of stones which possess hygroscopic properties. These substances are generally connected with one arm of a sensitive balance, the rise or fall of which measures its humidity. In addition to the source of error these bodies have in common with those which we have reckoned under the first class, they have this additional defect, that they are tardy in acting; *i. e.* they do not immediately follow the change in the condition of the atmosphere, but require some time to absorb and give out moisture, and especially they show but slowly a transition from a state ot less to one of greater dryness.

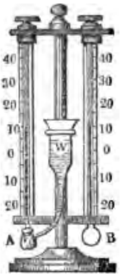
The third class, or hygrometers properly so called, depend on the combination of heat which accompanies the evaporation of a fluid, and the consequent deposition of the vapour contained in the atmosphere. These are the only hygrometers which can fulfil all the conditions required.

Le Roy first suggested the filling a glass with water, at the same temperature as the ambient air, and then cooling it by dropping in pieces of ice, until the outer surface of the glass began to be dim with the deposit of aqueous vapour. The difference between the temperature of the air and that of the water would, he said, show how many degrees the air must be cooled before the vapour it contained would be at its maximum density; the greater the number of degrees which this difference amounted to, the smaller the quantity of vapour in the atmosphere; consequently, the drier the atmosphere. Were the air completely saturated with moisture, the two temperatures would exactly agree, and the slightest fall in the temperatures of the water would instantly cause a deposit on the glass. The point at which the vapour contained in the air begins to be thrown down is called the *Dew Point.* For instance, if we suppose the temperature of the air to be 77°, and the dew point to be 54½°, then the atmosphere contains such a quantity of vapour as would be at a maximum density at 54½°. Now by Table XII. the tension of aqueous vapour, at this latter temperature, is 0·442; but this is the tension which it has in the atmosphere, at the temperature we have supposed, viz. at 77°, for the heat has merely rarefied the vapour, without imparting to it any greater expansive force. Now, had it been at its maximum density, under this temperature, by our table, its tension would have been 1·000; whence, in the instance we have supposed, the air contains $\frac{0\cdot442}{1\cdot000} = 44$ per cent. of the quantity of vapour it might have been charged with at that temperature. Although this experiment does not give strictly correct results, yet it has led the way to a more exact mode of hygrometry than had before been known.

Daniell's sulphuric æther hygrometer and *August's psychrometer* are instruments which act on the principle we have just explained. The last-named apparatus leaves little to be desired, as it enables us to ascertain the tension of the vapour contained in the atmosphere, the dew point, the point at which the atmosphere would be saturated, and hence the absolute weight of the vapour contained in any particular volume of air.

The *psychrometer* consists of two very delicate mercurial thermometers, which exactly correspond, divided into fifths, or even into tenths, of degrees (A and B, *fig.* 119.), the scales ranging from about — 25° Cent. (— 13° Fahr.) to + 40 Cent. (104 Fahr): they are both fixed in a frame, in a similar position, about 3 inches apart. The ball A is surrounded with muslin, which is continually moistened by means of a thread of cotton attached to it. the other end hanging in a cup W filled with distilled water; the other bulb is kept dry. As the water evaporates which surrounds the bulb of the damp thermometer in a thin film, the mercury begins to fall; and the drier the air, the more rapid its descent, as the evaporation will be more rapid. When the air around the bulb is saturated with moisture, the mercury will become stationary, and the point at which it rests will be the dew point, or condensation point. The greater the difference between the altitudes of the dry and moist thermometers the drier must the air be, or the farther is the vapour it contains from being at its maximum density. The difference between the heights of the two thermometers will be *nil*, if placed in an atmosphere containing aqueous vapour at its greatest density. From the degrees of heat shown by the two thermometers, as in the example given above, we can determine the expansive force of the vapour, and its amount per cent. in the air. The two following formulæ, constructed by Professor August, will give these values with great accuracy; and in them regard is paid to the altitude of the barometer at the time of the observation.

Fig. 119.



$$\text{I. } x = \frac{e - 0{\cdot}558\,(t - t')\,b}{512 - t'},$$

and

$$\text{II. } x = \frac{e - 0{\cdot}558\,(t - t')\,b}{572 - t'};$$

x being the tension required of the vapour in the atmosphere in Paris lines; e the tension in Paris lines, which by Table XII. corresponds with the temperature of the moist thermometer; t that of the dry and t' that of the moist thermometer, in degrees of Réaumur's scale; and lastly, b, the altitude of the barometer in Paris lines. Formula I. serves for temperatures above 0°, and II. when the damp thermometer is covered with ice, *i. e.* for temperatures under 0°.

To economise the time which would be consumed in calculating by these or other formulæ, several philosophers have constructed tables, which give the results for every degree of the psychrometer.

§ 418.

This property of hygroscopic substances of absorbing moisture from the atmosphere and from other bodies in contact with it, is used for other purposes besides meteorological investigations. Philosophers and chemists avail themselves of it frequently to dry the air and other bodies contained in receivers, and also for freezing gases from the humidity with which they are charged. The substances most generally employed for this purpose are heated chloride of calcium, and concentrated sulphuric acid, (compare *Experiments* 3 and 4. § 405., and the method of determining the point of greatest dryness in a hair hygrometer, described in the preceding section), which are either placed in the close receiver, or else the gas to be dried is made to pass through them. These substances are not available for drying on a large scale; for instance, for making and preserving dry, vessels which contain articles that would be injured by damp, such as provisions or gunpowder. Generally speaking, if a strong draught of air can be sent through such vessels, the air they contain will be speedily freed in great measure of its moisture. If this is not practicable, the chamber or vessel must, according to its dimensions, have a sufficient quantity of some hygroscopic substance enclosed in it to absorb the moisture; burnt lime is often used for this purpose. The air itself, when deprived by heat of its moisture, is a most effective agent, absorbing the vapour they contain from all bodies with which it comes in contact, to saturate itself with the quantity of vapour answering to its own temperature.

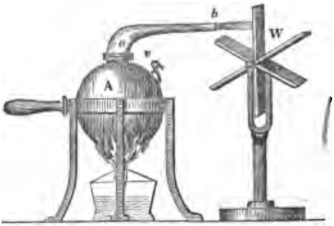
VII. APPLICATION OF STEAM TO MECHANICAL PURPOSES.

§ 419.

In modern times the application of steam to mechanical purposes has become increasingly varied and extensive, and consequently the part it performs in the different departments of industrial life is of growing importance. Undoubtedly the greatest service it renders is by its expansive force, as used in the *steam engine.* The considerable amount of both free and latent caloric (§ 404.) it contains, is employed in *drying by steam,* both in heating rooms and drying goods. The solvent power of steam above the temperature of 212° is made use of in the various kinds of *apparatus for cooking by steam,* besides being applied in other cases to soften or dissolve solid bodies.

One of the most simple pieces of apparatus for illustrating both the mechanical and thermal properties of steam is the *steam globe,* or *aeolipila* It consists of a hollow sphere of copper or brass (A, *fig.* 120.), about 3 or 4 inches in diameter. The aperture *a* serves partly for introducing the liquid, from which the steam is to be raised; and partly for screwing on different curved tubes, as occasion may require, from whose mouth *b,* the steam issues. When the aeolipila is about half full of water, screw on the steam pipe and place the apparatus over a spirit lamp, to raise the fluid within to a boiling temperature. To guard against the risk of bursting, it is well to furnish the sphere with a safety-valve *v.*

Fig. 120.



The following experiments will show the expansive and propelling forces acquired by the steam.

First Expt. Let the steam of the boiling water, as it issues from *b,* inpinge against the vanes of a wheel, W, that turns readily upon its axis; the vapour will acquire such force as to impart a rapid rotatory motion to the wheel.

Second Expt. Give to the steam tube such a curvature as is represented in *fig.* 121.: but instead of filling the vessel with water, use spirit of wine, and its vapour as it issues from *b* will act upon the flame of the spirit lamp, like the blast of a blowpipe, and give it such an intensity that glass and several of the metals will be melted by its heat.

Fig. 121.

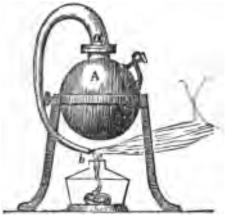
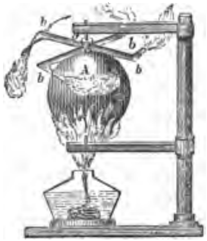
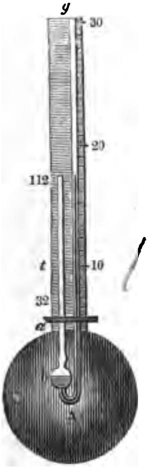


Fig. 122.



Third Expt. Provide the aeolipila with an axis about which it may turn (*fig.* 122.), and give to the tube *a b* the form shown in the diagram, and you will have precisely the apparatus invented by Hiero of Alexandria, 120 B. C.; the steam will escape in a direction tangential to the axis; and the reaction caused by its emission will generate motion in an opposite direction, the rotation of the ball depending on the same principle as that of Segner's machine, explained in § 165.

Fig. 123.



On the opening *a*, *fig.* 123, screw a barometer tube *b g*, instead of the steam-pipe; this barometer-tube will serve the purpose of a manometer (§ 200.), and show the increased tension of the steam attendant on an increase of the temperature. To effect this, the thermometer *t* is fixed beside the barometer-tube, its bulb descending into the space filled by the steam, the heat of which it therefore indicates. The expansive force or tension of the steam will be measured by the height to which the column of mercury rises in the barometer-tube, whose cup *b* should contain such a quantity of quicksilver as would suffice to fill the whole of the tube. To the mercurial column supported by the steam add the altitude of the barometer, at the time of the observation, and the sum of these two altitudes will express the expansive force of the steam, which answers to the temperature shown by the thermometer.

By means of the same apparatus we can investigate the thermal properties of steam.

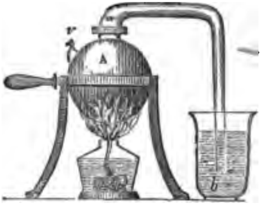
Fifth Expt. Allow the steam to issue from the steam-tube into the open air, and a portion of it will be condensed and rendered visible in consequence of its giving out some of its caloric to the surrounding atmosphere; extremely minute bubbles will be formed, which are filled with humid air enclosed in a thin film of aqueous vapour: these will be borne along by the air like aerostats.

Conduct this stream over a hot metal plate, or over some burning charcoal, and it will cease to be visible, because no absorption of its heat takes place, and consequently there is no condensation of the steam into water.

Sixth Expt. Now receive the current of steam on any cold body, as a plate of metal or a glass receiver, and the aqueous vapour will be deposited over the surface in the form of water, and the metal or glass will be rendered perceptibly warmer by the heat which has been liberated.

The same result follows if the steam-pipe be conducted, as is shown in *fig.* 124., so as to terminate in a vessel of water. The steam is instantly condensed, so that the vapour, which is emitted at *b* disappears instantaneously without rising to the surface in the form of air bubbles. The water in the vessel becomes gradually heated, as may be seen if a thermometer be immersed in it, until at length it reaches the boiling point. This experiment may serve to show indubitably the great quantity of latent heat contained in steam, although it does not furnish us with the means of exactly measuring its amount.

Fig. 124.



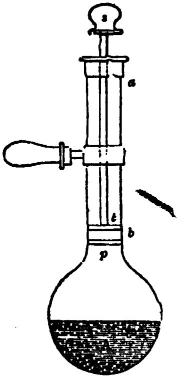
§ 420.

The *steam-engine* is unquestionably one of the most important, as it is one of the most useful, inventions of the eighteenth century. The principle on which it acts is this, that steam at a temperature exceeding that of boiling water possesses so great an expansive force (compare § 410. and Tables XII. and XIII.) as to propel bodies against which it is directed, such bodies returning to their original position when the steam by being condensed is deprived of this force.

This fundamental action of steam, which is made use of in the working of every variety of steam engine, may be illustrated by the following simple apparatus:—

Expt. The arrangement consists of a glass tube (*a b*, *fig.* 125.), open at one end and enlarged at the other into the bulb A; a piston *p*, surrounded with worsted or cotton thread, saturated in grease to render it steam-tight, is worked up and down by means of the piston rod *t s*. — Place some water in A, and hold it over a spirit lamp till it begins to boil, the steam thus generated will elevate the piston *p* to the upper end *a* of the tube. — Plunge the apparatus in some cold water, the steam will be condensed, a vacuum will be formed beneath the piston, and the superincumbent pressure of the atmosphere will drive down the piston to the lower part of the tube.

Fig. 125.



The principal parts of every steam engine are the *boiler* and *cylinder*: in the former is placed the water which it is intended to convert into steam, and in the latter is the *piston*, which is to exert the motive power. Besides these principal parts of every engine there are many mechanical contrivances, by which the former are connected, and by means of which the entire working of the machine is regulated, and the motive power applied in the desired direction.

Various forms have been given to the boiler, which is made of the very strongest wrought iron; sometimes it is of a spherical figure, sometimes like a trunk with a rounded lid, most generally however it is cylindrical: in some cases it consists of a number of tubes connected together, this construction having been adopted to lessen the risk of explosion. It is filled with water to a certain height, above which is the space where the steam is to accumulate; beneath the boiler is the furnace for heating the water. The boiler and cylinder are connected by means of the *steam-pipe*, by which steam is conveyed from the former to the latter; a second pipe, called the *feed-pipe*, keeps up a supply of water in the boiler, to make up for what is abstracted in the form of steam. Appliances of a more complicated nature than we have described above are made use of in most engines, for regulating the supply of water and showing the quantity present at any moment in the boiler, so as to avoid the risk of its bursting either by the expansion of the steam, or by the pressure of the atmosphere. There is also generally some contrivance for showing the degree of expansion attained by the steam. — All these matters will be explained at greater length in the observations that follow these paragraphs.

The *cylinder*, which stands erect, is of cast-iron, hollow, and polished inside: within it there works a steam-tight *piston* having an iron rod, called the *piston-rod*, which projects above the cylinder. It is on this piston that the steam acts, and the primary movement thus generated is a mere ascent and descent of the piston in the cylinder. To ensure the complete effect of the steam on the piston, the cylinder both above and beneath is made perfectly steam-tight; for which end the piston rod is made to pass through a *stuffing-box*. The other parts of the machinery are immediately connected with the piston-rod, so that by it the action of the whole is regulated.

In many engines there is also a second cylinder, called the *condenser*, connected with the former: in it the steam, after having acted on the piston, is condensed by a jet of cold water, and its expansive force, which would prevent the return of the piston, is destroyed in that direction in which the piston is to move.

Steam engines may be ranged under three classes, according to the system adopted in their construction; viz. according to the mode in which the steam-power moves the piston in the cylinder; according to the expansive force of the steam used; and lastly according as the steam is or is not condensed.

In the first class there are three varieties, viz.

1.) *The single acting steam engine*, in which the piston is driven only one way by means of the steam, and returns partly by the preponderating weight of that portion of the machinery and partly by the atmospheric pressure acting on the upper surface of the piston, the part of the cylinder beneath the piston being a vacuum. In a machine of this kind only half the motion of the piston is used as an effective force, namely, its descent; for in its ascent its operation is suspended. As the descent of the piston is effected mainly by the pressure of the air, these engines have been termed *atmospheric engines*.

2.) *Double acting engines*, in which the steam is effectively employed both in the ascent and descent of the piston in the cylinder, being admitted alternately above and below the piston; these machines have an unintermittent action.

3.) *Engines on the expansive principle* differ from the two preceding varieties in this, that whereas in them the supply of steam is maintained in the cylinder, during the entire ascent or descent of the piston, in engines on the principle of expansion the steam is cut off, when the piston has performed one half or thereabouts of its distance, the expansion of the steam driving it through the remainder.

Under the second class we may reckon:

1.) *Low pressure engines*, or those in which the expansive force of the steam employed but little exceeds the pressure of the atmosphere; and,

2.) *High pressure engines*, in which the water is heated till it acquires an expansive force of from 2 to 10 atmospheres.

Lastly; they may be distinguished as

1.) *Condensing engines*, in which the steam having raised or depressed the piston, as the case may be, is condensed either mediately or immediately by coming in contact with cold water; and

2.) *Non-condensing engines*, in which the steam when used is allowed to escape directly from the cylinder into the open air.

Besides those named above, there are many other varieties of the steam engine, which however do not constitute a distinct system, but are generally named after the inventor of the peculiarity of construction by which they are distinguished.

According to the definition agreed upon, of what constitutes a steam engine, we must frame our answer to the queries — To whom are we indebted for the fundamental idea of this important piece of machinery? — When and where was it first formed? — If the name of steam engine is to be given to any contrivance by which steam is made to communicate motion, then we are indebted for this invention to Hiero of Alexandria, 120 years B. C., for he first constructed the aeolipila, or rotating steam ball (described in the third experiment, § 419.). The discovery of Denis Papin in the 17th century was far more important in its bearing on our knowledge of the mechanical force of steam. He not only used the solvent power of steam in the *digester*, since called by his name, but furnished this apparatus with a safety valve: he expressed his firm belief that vessels might be propelled and shots thrown by means of steam; but he constructed an apparatus in 1687, described at the beginning of this paragraph, which may fairly be regarded as the type of the action of the ascent and descent of the piston in its cylinder.

The first machine really worthy of the name of steam engine was Newcomen's, made in 1705. It was a simple low pressure engine, in which the piston was elevated by steam; on reaching the top of the cylinder, the steam was condensed by a jet of cold water, and the descent of the piston was effected by the downward pressure of the atmosphere. In this machine steam was only indirectly the cause of motion, as by its condensation a vacuum was formed below the piston, which was driven down by the atmospheric pressure: hence its name, *atmospheric steam engine.*

The most numerous and important improvements introduced into the construction of this machine, are owing to Watt, by whom it has been brought almost to its present state of perfection. He first conceived the idea of cooling the steam in a separate chamber, which he called the *condenser*, by which contrivance he avoided lowering the temperature of the interior of the cylinder, and so considerably economised his steam power. He did not at once avail himself of the expansive force of steam to generate motion but for some time drove the piston by the atmospheric pressure exerted on the upper surface of the piston. Watt was the first to perceive the inconvenience of using a force which was not capable of being modified; he was also the first to provide a remedy for this defect in his engine, by making the cylinder air tight above; he then admitted steam above the piston, which was driven down by the pressure of the steam, instead of by that of the atmosphere. When the piston arrived at the bottom of the cylinder, the steam was shut off, and at the same time a communication was opened connecting the upper part of the cylinder with the condenser; the steam rushing into this cold chamber instantly lost its elasticity, and the piston was at once raised by the weight attached to the farther end of the beam to which the piston-rod was fastened. When the piston had thus regained its original position, the communication with the condenser was closed, the steam was again admitted above the piston, and thus the piston continued to play. In this machine, known as the *single acting steam engine*, there is the same defect which is common with it to the atmospheric engine, namely, its intermitting action, because the piston in its ascent suspends the operation of the machine. Such engines were consequently available only where the suspension of the moving power was not prejudicial; as, for instance, in raising water from mines. This most serious defect was remedied by Watt's invention of the *double acting steam engine*, in which, as we have already remarked, steam power both raises and depresses the piston in the cylinder, by which means the engine's working is rendered continuous, and it is thereby made capable of imparting to machinery connected with it any kind of movement that may be desired. We shall now add a more detailed explanation of an engine of this kind.

Fig. 127.

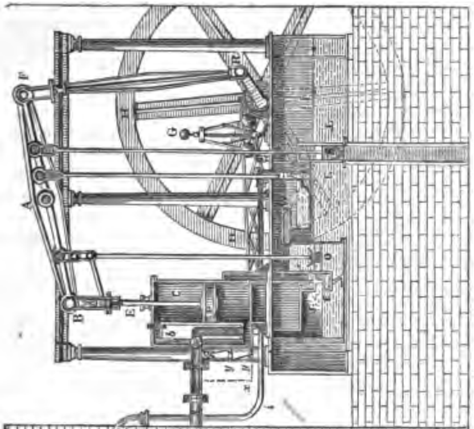


Fig. 126.

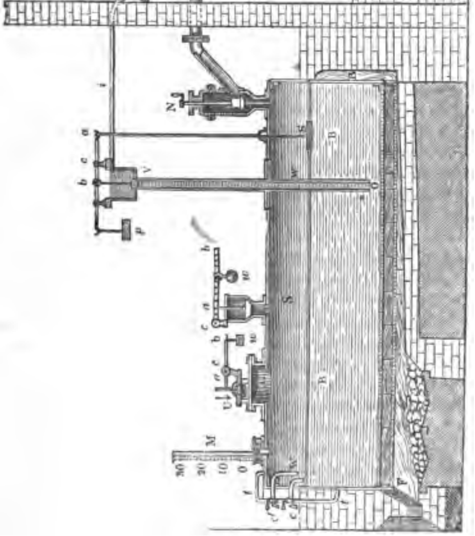


Fig. 126. represents the boiler and the parts belonging to it; *fig.* 127. the mechanism of the engine connected with it.

B B is a longitudinal section of a cylindrical or coffer-shaped boiler, with the furnace F F under it; W W is the normal height of the water, in the space S, above which the steam is accumulated.

Low-pressure engines are furnished with a *gauge*, to show at any moment the height of the water in the boiler. This instrument consists of a tube, communicating both with the water and with the space allotted to the formation of steam; the vertical part *t t* is of glass; and by the laws of hydrostatics (§ 156.), the water in the tube must stand at the same level as that within the boiler. In high-pressure engines, two *cocks* *c* and *c'* are inserted in the boiler; the former *c*, the *water-cock*, communicates with the fluid in the boiler; the other *c'*, called the *steam-cock*, terminates in the part allotted to the steam; when the water is at its proper elevation, on opening the cocks, water will issue from the lower one, and steam from the upper; if the boiler contain an insufficient quantity of water, steam will be discharged from both the cocks; if the supply of water be too great, then it will issue from them both.

It is of extreme importance that water should be uninterruptedly supplied to the boiler, to compensate for the waste occasioned by its conversion into steam. This object is attained by furnishing the boiler with a *feed-pipe*, the mechanical construction and working of which have been already explained in § 171. The water in the feed-pipe V O must necessarily stand at such a height, that the weight of the column of water, together with the weight of the atmosphere, may serve to counterbalance the expansive force of the steam. Thus, if we suppose the pressure of the steam to exceed that of the atmosphere by 1 lb. on the square inch, then the column of water in the feed-pipe must be $32 : \frac{9}{11} = 26\frac{2}{11}$ in. (for 1 cubic inch of water weighs $\frac{9}{11}$ of a half-ounce, and 32 half oz., or 16 oz. = 1 lb.) or something more than 2 feet high; if the excess of pressure be 2 lb. per inch, the height of the column must be more than 4 feet, and so on. If the steam exerted a pressure of 2 atmospheres, a column of water would be required 32 feet in height; hence this kind of feeder is available only in low-pressure engines, in which the tension of the steam at most is not more than 4 lbs. per square inch greater than that of the atmosphere; equal to about $1\frac{1}{4}$ atmosphere. In high-pressure engines, which would require feeders of unwieldy dimensions, the supply of water is kept up by means of pumps worked by the engine itself.

In order still further to show at any moment the tension of the steam in the boiler, a *barometer-gauge*, or manometer M, is connected with it. A full description of this instrument is given in § 200. It is depicted on a larger scale in *figs*. 136 and 137. Vol. I. page 228.

To secure the boiler from explosion caused by the steam contained in it, it is not enough that we should be able to know, from time to time, the pressure of the steam in the boiler; for it is very possible that, for want of the proper degree of care on the part of the engine-man, it might be allowed to acquire too great a force; hence provision is made for the escape of the steam by the *safety-valve*, so soon as its pressure shall exceed the maximum pressure for which the boiler has been constructed. Generally speaking, this apparatus consists of a conical valve in the upper part of the boiler opening outwards, as has been shown already in *figs*. 117 *a* and *b*. (For a full description, see § 412.) Sometimes the valve is loaded by means of weights suspended to the end of a lever; sometimes the weight is laid immediately on the valve itself, which in that case is covered with a metallic capsule to prevent its being overweighted, and the metal is pierced with holes to allow the steam to escape. In low-pressure engines, whose boilers have an inconsiderable thickness of iron compared with that of which the high-pressure engines are made, the external pressure of the atmosphere might prove destructive, if by any means the expansive force of the steam within fell much below the pressure of the atmosphere without. To guard against such an occurrence, which might happen if the quantity of steam, and consequently its tension, were too much diminished by an excessive fire, there is attached to these engines a valve U opening inwards, connected with a lever *a c b*, at the extremity of which is suspended a weight *w*, that exerts a force of 4 lbs., or thereabouts, on the square inch; so when the excess of the weight of the external air is more than 4 lbs. over the pressure of the steam in the boiler, the valve opens, and such a quantity of air is admitted as altogether removes the danger of compression. In high-pressure engines this contrivance is unnecessary, the plates of which their boilers are composed being of such a thickness, that a force of 15 lbs. on the square inch does not exert any prejudicial influence upon them. — Sometimes boilers have been constructed with holes that have been closed with some alloy that fuses readily (§ 401.), and then, on the boilers becoming too much heated, the alloy melts, and the steam escaping, all danger of explosion is avoided as effectually as when the ordinary safety-valves are used. Explosions have occasionally happened, even after every precaution has been taken. These are probably owing to Leidenfrost's phenomenon. (§ 404.) When through any negligence on the part of the engine-man, or through any defect in the feeder, the water in the boiler has been allowed to sink so low, that part of the surface which is exposed to the action of the fire is rendered red-hot, being no longer in contact with water; if then water is poured into the boiler, we have precisely the combination of circumstances requisite for the production of the phenomenon observed by Leidenfrost; the water on coming into contact with the red-hot metal does not boil immediately; but when the temperature of the latter is sufficiently lowered, steam is generated with such intensity that it cannot escape with adequate velocity by the safety-valve, and the consequence is that the boiler bursts.

As water is obtained perfectly pure only by distillation, that which is used in the boilers of steam-engines always contains a greater or less quantity of foreign matter, such as carbonate or sulphate of lime, &c., which gradually forms a deposit at the bottom of the boiler, and being hardened by the continued action of the fire, forms a stony coating or *crust*; this, in part, tends to retard the heating of the water; it also causes the boiler to be more quickly injured by the fire. When the boiler is of sufficient dimensions, a hole L is left, large enough for a man to go down by to clean it out; this aperture is, of course, secured at other times by a valve; in tubular and other small boilers, some other contrivance is adopted for cleaning them from this crust.

Lastly, the boiler communicates with the cylinder by the *steam-pipe s s*; the aperture to which is closed by a valve N, that is not opened till the steam has acquired the requisite degree of pressure.

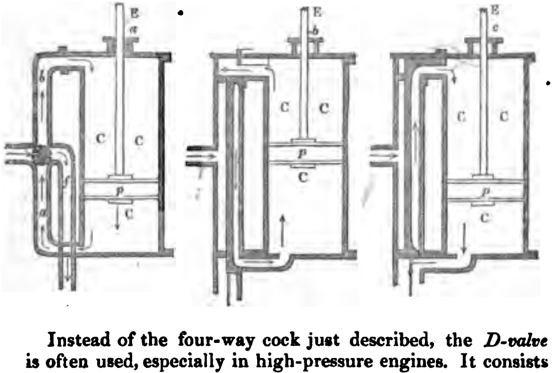
The steam is conveyed along this pipe in the direction indicated in *fig.* 127. by the arrows, either through *a* or *b*, by the *four-way cock* into the cylinder C.

The alternate admission of the steam above and below the piston is regulated by a system of levers *y*, to which is attached a handle or *spanner*, connected with some part of the machinery, the elevation and depression of which turns the cock.

The steam thus admitted above and below the piston P drives it up and down in the cylinder; the piston-rod E is connected at one end with the *beam* B F, a two-armed lever moveable about its fulcrum A; at the other or working-end of which F is the *connecting-rod* F R, whose lower end R is attached to the crank by a pivot; it is this rod which sets in motion the *fly-wheel*, that drives any machinery connected by a system of tooth-and-pinion work with its axis: the equal motion of the machinery will be owing to the inertia and momentum of this wheel. (§ 27.) When the steam has discharged its office of elevating or depressing the piston, as the case may be, it is carried off by the *eduction-pipe ff* into the *condenser* I, which stands in a cistern L of cold water; the steam on entering the condenser is instantly converted into water by a jet of cold water from the *injection-cock.* The warm water thus accumulating in the condenser as also the air carried in with it, is pumped out by the *air-pump* O into the *hot-well* W, whence the *hot-water pump h* raises it through the feed-pipe *i i* to the feeder, by which it is returned to the boiler. Lastly, the *cold-water pump* S supplies the cistern L with the requisite quantity of cold water. As the diagram indeed shows, all these pumps are connected with the beam, and are worked by it.

The diagram represents the cock *c* in such a position as to allow the steam to enter from the boiler and pass down the tube *a* below the piston, whilst the portion above the piston escapes by *b* through *f* into the condenser. When the cock has made a quarter turn, it will be in the position represented in *fig.* 128 *a*; the steam will then pass through *b* above the piston, and that which is below it will escape through *a* and *f* into the condenser.

Fig. 128.



Instead of the four-way cock just described, the *D-valve* is often used, especially in high-pressure engines. It consists of a hollow semi-cylinder connected with the exterior of the cylinder, and furnished with a slide, moved up and down by the machine, so as alternately to admit the steam above and below the piston. *Fig.* 128 *c* represents the position of this valve when steam is admitted above, and *fig.* 128 *b*, when admitted below, the piston.

To insure a steady movement in the engine, the *governor* G (*fig.* 127.) is added. This apparatus, also the invention of Watt, consists of a vertical iron rod, from the upper part of which are suspended two other iron rods, loaded at the ends with heavy balls, something like pendulums. There are various modes by which the governor is connected with the axis of the fly-wheel, so as to receive from the latter a rotatory motion about its axis, in consequence of which the balls acquire a tendency to fly off proportionate to the velocity with which they are made to revolve. An iron ring *z*, which slides freely up and down the perpendicular rod, is connected by two strong wires with the pendulum-rods. This ring or collar is made to rise or fall, as the centrifugal force of the balls causes them to recede from, or approach towards, the perpendicular. A system of levers is connected with this ring, joining it with the steam pipe; the size of the diagram precludes our doing more than indicating its position by the dotted lines *x x x*. By this arrangement a valve, termed the *throttle-valve*, is made to regulate the admission of the steam, the ascent of the balls causing the levers more nearly to close the valve, and so diminish the quantity of steam received into the cylinder; their descent, having the opposite effect of opening it more widely, admits the steam more freely.

Non-condensing engines are much more simple in their construction than Watt's double-acting condensing-engine, which we have just described, as in them all the arrangements for the condensation of the steam are dispensed with. They must necessarily be double-acting, and must work at *high pressure;* as, instead of condensing their steam after it has pressed the piston one way, they allow it to escape into the air; the piston must therefore on its return be propelled with a force exceeding the pressure of the atmosphere. — Engines of this kind were first constructed by Trevithick in England and Evans in America. — Condensing-engines may also be made to work at high pressure. Their mechanism in the main resembles that of Watt's double-acting engine, already described. They will require a larger jet of water in consequence of the higher temperature of their steam, and a force-pump must be used that will overcome the pressure of the steam in the boiler, in order to maintain the requisite supply for the production of the steam.

Mr. Perkins's modification of the *steam-engine* is deserving of a short notice, as so much was anticipated from its performances at first, although up to the present time no very satisfactory result has demonstrated the peculiar advantages of this machine. The distinguishing feature in this engine is the mode in which the steam is produced, as it has no proper boiler, but merely a very strong cylindrical vessel, to which the inventor gave the name of *generator*, which is completely filled with water, and then placed in the fire till it acquires a temperature of from 400° to 450° Fahr. Now, if an additional quantity of water be driven by means of a force-pump into the generator, a portion of the heated water will be discharged through a valve, and instantly converted into steam, having, according to Mr. Perkins's estimate, a pressure equal to that of about 35 atmospheres, that is to say, of about 500 lbs. on the square inch. Steam at this extremely high pressure is then admitted into a cylinder only 18 inches long and 2 inches wide, the piston in which would perform 200 strokes in a minute, and exert a force equal to 10-horse power. Steam-engines of this kind, according to their original construction, would occupy but little room, and would consume only $\frac{1}{9}$th as much fuel as one of Watt's double-acting engines; but when made of these small dimensions, they were of little practical utility; and if on a large scale, it is difficult to secure the requisite strength in the materials, especially in the generator, which is exposed to so intense a heat, for the great increase in the temperature proportionally weakens the cohesive force. There is also the further difficulty in procuring any unctuous matter to lubricate the piston at a heat which would convert our ordinary unguents into vapour. These steam-engines excited the greatest share of attention, in consequence of the notion that the expansive force of steam might be substituted for that of gunpowder in military operations. The principal points in which these steam-guns differ from those ordinarily used in warfare are, that, owing to the duration of the propelling force, they enable us to discharge in a short time a great number of balls and, in consequence of the facility with which the tube may be turned on a swivel, the shower of balls may be directed in any direction that may be desired. At first it seemed as if the discovery of this new engine would lead to as great a revolution in the art of war as the invention of gunpowder itself had already produced. The experiments which have been performed both in England and France with a view of settling this question, have established the fact, that, as at present constructed, they are ill adapted for use in war. It was found that these engines required complicated and ponderous apparatus, even when their size was only such as fitted them to discharge small shot; that a considerable time must elapse before the steam attained the necessary force to effect the discharge; and lastly, that the force of percussion attained by the balls was less than that of similar balls projected by means of gunpowder. Prechtl, in his Jahrbuch, d. K. K. polytechn. Instit. zu Wien ix. 1—42., has demonstrated that the effect of steam, under those circumstances in which it has yet been found, is not equal to that of gunpowder when applied to large shot.

The great superiority of steam over every other motive power is this, that, provided we can have the necessary fuel and water, we can apply it to any point we desire, and within pretty extensive limits we can increase or diminish its force. It can be applied with great advantage in circumstances where other motive powers, water-power especially, would be inadequate to perform the duty required, or insufficient and uncertain in its supply. If we compare, in an economical point of view, steam and water power, we must be guided in our decision, not merely by the original outlay or the actual cost of working the two powers, for in respect of original expenditure water will probably be the more costly, and the cost of working it small; whereas, the steam-engine, if cheaper in the first instance, entails a permanent expense. If, however, a regular and uninterrupted force is wanted, as in mining operations, navigation, many kinds of manufactures, &c., then the steam-engine has a decided superiority over water-power in its greater regularity and certainty; and unless, which is rarely the case, the supply of the latter is both constant and equal, it is ill suited for these purposes. If the work required to be done is uncertain in amount and irregular as to time, so that the furnace would have to be lighted and fire extinguished frequently, then the great expense which would be incurred would render water-power preferable. Many circumstances would contribute to decide the choice in favour of the one or other kind of engine, such as the purpose to which the engine is to be applied, the situation where it is to be erected, the cost of fuel, &c.

The older sort of *atmospheric engines*, working at low pressure, are very well adapted, where fuel is cheap, to raise water from mines, to supply towns with water, and to elevate any great masses of water. Indeed, their mechanism is extremely simple; they can be put up, and, when necessary, can be repaired with greater ease than engines that work by the pressure of the steam. If made of small dimensions, their useful effect is insignificant, as the relative consumption of coal greatly exceeds their effect if the cylinder be less than 25 inches in diameter.

Single-acting steam-engines, in which the piston is driven one way by the pressure of the steam, in consequence of their mode of acting, are available only for elevating water and performing that kind of work which is not impaired by the suspension of the power during the return of the piston. Generally speaking, their useful effect is not greater than that of the ordinary atmospheric engines; but their consumption of fuel is only one-third or half as much, and the quantity of water required for injection is also less.

The *double-acting steam-engine*, of which we have already given a detailed explanation, is best adapted for general purposes, and for accomplishing those performances to which the steam-engine is applied: hence of stationary engines this is the kind in most general use. The movement of this engine is extremely regular, for which reason it is well suited to drive mill-work, looms, &c., where the greatest attainable regularity in the performance is desired. The only limit to their adoption is, that there should be a facility for obtaining the requisite amount of water for injecting. These engines work with a smaller cylinder and consume less fuel than the single-acting engines. Their useful effect is greater, as the whole of the steam pressure is used in working the machine. They have been applied with complete success to propel large steam-vessels which were formerly believed to require high-pressure engines.

Machines that work by *expansion* require still less fuel than Watt's double-acting engines without expansion, as with an equal consumption of fuel they perform nearly twice the duty of the latter; and even if the expansive force of the steam is partially used in the latter, yet these engines will even then do half, or at least one-third, as much more. Their force may also be increased at any time, provided that the steam is not already at its greatest expansive force. This cannot conveniently be done with the double-acting engine. These advantages are counterbalanced by this drawback, that they are suited only to produce rectilinear motion, as the stroke of the piston is not performed uniformly; and if their movements were to be equalised by means of a fly-wheel, it must necessarily be of such extreme dimensions as would render its use objectionable. Besides, these engines are more complicated in their construction, and, consequently, more expensive in the first instance, as well as more likely to get out of repair, and more difficult to mend. For these reasons they have been less generally adopted, and in England have almost entirely ceased to be used.

All *high-pressure* non-condensing engines are, as respects their mechanism, far more simple than the preceding. They occupy less room, and are the lightest made. Their consumption of fuel is, however, the greatest. They are applied advantageously in all cases where space is an object, and when the water requisite for condensation cannot be had, or can be had only at an undesirable sacrifice of power. Their most extended application has of late been in locomotive engines, whose piston-rods are connected immediately by means of cranks with the working-wheels, by whose adhesion to the ground the load is propelled. In these engines the boiler and furnace are arranged so as to generate steam of high pressure in the least possible time. For every horse-power they weigh from 13 to 15 cwt., or about half as much as a double-acting steam-engine weighs. The original cost of stationary non-condensing high-pressure engines is less than that of condensing engines; but the expense of working them is greater. Their effect is no greater, and their boilers are much more liable to burst, which generally happens either through the steam being allowed to acquire an excessive expansive power, or through some irregularity in the supply of water. When local circumstances will admit, it is sometimes convenient to apply the waste steam of these engines to heat water for drying apparatus, or for warming rooms. High-pressure condensing-engines, working also by expansion, are more economical than the non-condensing engines, or than either the atmospheric or the single-acting engine, provided only that the requisite supply of water can be readily obtained, and that its somewhat irregular action is not a serious drawback. These engines are frequently used in steam-boats, where water for condensation can be secured with the greatest facility.

The number of steam-engines is annually increasing at a rapidly progressive rate. Fifty or sixty years ago there were not 100 in use; at the beginning of the year 1838, their number was estimated at about 200,000, equivalent to the labour of about 4,000,000 horses. The incessant extension of lines of railway will call into existence a growing number of additional engines.

§ 421.

The performance of a steam-engine is generally measured by the amount of its horse-power. This unit of power dates from the first application of the steam-engine in England to raise water from the mines, a work formerly accomplished by animal labour:

their performances were estimated by the useful effect one horse would produce during the ordinary duration of his work (§ 28.). This dynamic unit has hence been termed horse power; to it various values have been affixed, but generally it is now estimated as a force that would suffice to raise a weight of 33,000 lbs. a height of one foot in one second of time.

In France a new dynamic unit has been adopted, viz. the force which would raise 100 kilogrammes per minute through a height of one metre; the simplicity of this mode of reckoning will be a recommendation wherever the decimal system of weights and measures has been adopted. It may be hardly needful to remark that the nominal value of horse-power does not coincide with the actual performance of the animal, as the number of hours that animal exertion can be continued is limited in a manner that steam-power is not, consequently we are not to suppose that in useful effect 20 horses could be substituted for an engine of 20-horse power.

The gross effect of a steam-engine is found from the superficial content, or from the diameter, of its piston, the pressure on the piston, and its velocity. The last-named element is determined by multiplying the height of the piston-rod in feet into the number of strokes it performs in a minute, a whole stroke being both the ascent and descent of the piston in the cylinder, its motion either way being reckoned as a half stroke. From the gross effect thus found deduct the power spent in overcoming friction and in first communicating motion to the various parts of the engine. A further allowance has to be made on the account of the resistance of the uncondensed steam in the condenser; in non-condensing high-pressure engines this drawback is reckoned to be equal to one atmosphere. Hence the *useful effect* of any engine is found by making all these deductions from its gross effect (1), and dividing the remainder by the dynamic unit.

1.) The amount of power lost in different engines depends very much on their construction; in atmospheric engines it amounts to 0·52; in single-acting and non-condensing high-pressure engines it is 0·4; in double-acting engines 0·368; commonly one-third is assumed as a mean.

The following example of the mode in which the effect of a double-acting steam-engine is calculated may perhaps serve to illustrate the preceding remarks: — Suppose the expansive force of the steam in the boiler to be equal to $1\frac{1}{2}$ atmosphere, and the temperature in the condenser 102°, then the force of the steam in it will, by Table XII., be 2·21 inches $= 0\cdot074$ of an atmosphere; hence the effective pressure of the steam on the piston is $1\cdot5 - 0\cdot074 = 1\cdot426$

atmosphere. From this deduct $\frac{1}{3}$ for loss of power, and the useful effect with which the engine works will be $1·426 \times \frac{2}{3} = 0·95$ of an atmosphere. Then assume the atmospheric pressure per square inch to be 15 lbs., and we shall have $0·95 \times 15 = 14\frac{1}{4}$ lbs. for the pressure exerted on every *square* inch of the piston's surface, or $0·785 \times 14\frac{1}{4} = 11·2$ lbs. on a *circular* inch. Next, let the piston be 20 inches in diameter, and the power with which it works will be $20^2 \times 11·2 = 4480$ lbs.; if the length of the piston-rod be $3\frac{1}{2}$ feet, and it performs 64 half strokes per minute, its velocity will be $64 \times 3\frac{1}{2} = 224$ feet. This machine would consequently raise $4480 \times 224 = 1003520$ lbs. one foot in a minute, its horse power is therefore $\frac{1003520}{33000} = 30$.

Had it been a high-pressure engine working with steam at $4\frac{1}{2}$ atmospheres, the dimensions being the same in this case as in the preceding, the pressure on the piston would have been $3\frac{1}{2}$ atmospheres; and, after deducting the loss of power, its useful effect would have been $3·5 - 0·4 = 3·1$ atmospheres, or $3·1 \times 15 = 46·5$lb. per *square* inch, or $0·785 \times 46\frac{1}{2} = 36·5$ lbs., the useful effect on the *circular* inch of the piston. The engine would therefore work with an effective force of $20^2 \times 36·5 = 14{,}600$ lbs., and a velocity of 2·4 feet; it would therefore elevate $14600 \times 224 = 3270400$ lbs. one foot per minute, and it would have $\frac{3270400}{33000} = 100$-horse power.

The subjoined formula will give the horse power of an engine more readily and with sufficient exactness for ordinary purposes: —

$0·0000238\ d^2 V\ P = n$-horse power, *d* being the diameter of the piston in inches, V its velocity in feet per minute, P the pressure of the steam per square inch after the deduction is made for loss of power. By means of this formula we can find the value of *d*, V, or P, the other quantities being known.

The double-acting low-pressure engines generally work, after making the proper deductions, at a mean pressure of one atmosphere, with a force of $0·785 \times 15 = 11·7$ lbs. per circular inch, and with a velocity of 200 feet per minute. Every circular inch of the piston's surface therefore expresses a force of $\frac{11·7 \times 200}{33000} = \frac{1}{14}$th of a horse power; whence, on every 14 circular inches of the piston, there will be a force of one-horse power. An engine of 30-horse power would, by this calculation, require a surface of piston of $30 \times 14 = 420$ inches, and a diameter of $\sqrt{420} = 20 \cdot 4$ inches nearly.

In every steam-engine the quantity of fuel consumed in raising the steam of requisite pressure is an important subject to be considered. It is reckoned at so much per horse power, and depends partly on the kind and goodness of the fuel itself, partly on the size and construction of the engine, but principally on the arrangement of the boiler and grates. The most efficient fuel is good coal; next, the brown coal; then turf and wood.(1.) Large steam-engines of similar construction require less fuel than smaller ones; *i.e.* an engine of 10-horse power would not consume so much fuel as 10 engines of one-horse power each; generally speaking high-pressure engines use more coal than low-pressure engines. The latest experiments (1838) made in France on the consumption of coal, have given the following results, that low-pressure engines, on an average, consume for every horse power 3·8 kilogrammes of good coal per hour = 8lb. 6oz. 3dr. avoird., and that high-pressure engines consume 6·42 kilogrammes in the same time = 14lb. 2oz. 11dr. avoird.

§ 422.

The application of steam to the drying of substances and the heating of rooms depends on this property, that when it comes into contact with bodies cooler than itself it becomes condensed, and imparts to such bodies the greater part of its *heat of conversion*, which has been variously estimated at from 942° to 1007°, in raising water from 42° to 212°, and conversely in cooling steam at 212° to 42°. (§§ 404. 412.) To heat buildings, the steam is generated in a vessel, very much like the boiler of a steam-engine, whence it is conveyed by pipes into the large tubes by which it is proposed to heat the chambers; these large tubes, condensing the steam they contain, impart to the ambient air the caloric thus liberated. By a continuation of these pipes the steam, on its conversion into water, is conveyed back again to the generator. The pipes carrying the steam are made of some material that is a bad conductor of heat, to the point where it is desired that the process of warming should commence, and there they are joined on to metal tubes. This method of warming buildings whose dimensions are large, and which contain

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1.) If English coal be reckoned as 1, experiment has shown that Lüttich coal is equal to $\frac{2}{3}$ to $\frac{3}{4}$, Dresden at $\frac{1}{2}$, good brown coal at $\frac{5}{12}$, turf and wood at a mean of $\frac{1}{4}$, the weights of each of these kinds of fuel being equal.

many chambers, all to be maintained at an equal temperature, has the two great recommendations of accomplishing the desired object at a smaller expenditure of fuel, and without exposing the buildings to the risk from fire, to which they are liable when heated by the ordinary mode.

This method of heating by steam has been applied to the drying of gunpowder, by which the risks of explosion are greatly obviated.

As 1 lb. of steam at 212° would raise 1 lb. of water from 32° to 1004°, whilst the capacity of the atmosphere for heat is only 0·2669 that of water (See Table XI.), it follows that 1 lb. of steam at the above temperature would raise the temperature of 1 lb. of air at 32°, that is to say, of a volume of air 770 times that of the water, to $\frac{972}{0{\cdot}2669} = 3604°$; it would therefore raise the temperature of a volume of air $\frac{3604}{36} \times 770 = 77000$ times greater than the volume of the water up to 68°.

Clement states that his experiments have shown that, in the mild climate of England, the tubes ought to have a surface of 1·5 square foot adequately to warm a space of 100 cubic feet; that, in northern France and Germany, to warm the same bulk of air, there should be a surface of 1·66 square feet of piping.

§ 423.

We have already observed that steam is used to macerate, or even entirely to dissolve solid bodies: this it effects, partly by means of the great quantity of latent heat it contains when at a high pressure, partly by its elastic force, and partly also by the extreme minuteness of its particles and the readiness with which they move among each other; hence they are enabled to penetrate into the interior of the substances on which they act, for they are urged by an equal pressure in all directions, and the substances submitted to the operation of this force readily fall asunder in minute portions.

However varied the forms of the *apparatus for cooking by steam*, the principle on which they act is common to all. Generally speaking, they are constructed either so as to convey the steam, generated in a boiler, by means of tubes, immediately to the meat which is contained in closed vessels, or the tubes are made to go round the outsides of these vessels; sometimes high-pressure steam is used, and at others that which is generated at the ordinary boiling point.

The first application of steam in this way to culinary purposes was made by Papin, the inventor of the *Digester*, in the early part of the 17th century; in this instrument he heated water considerably above its boiling point, and converted bones to a jelly.

The solvent power of steam is applied with advantage to many purposes connected with the arts; in large establishments such as hospitals, barracks, &c. it effects a large saving in expenditure if the food be cooked by steam.

VIII. THE VARIOUS SOURCES OF HEAT.

§ 424.

Experience proves that the heat existing upon our globe is derived from various sources: of these the principal are, the *solar light;* the *change in the aggregate form of bodies,* their *capacity for heat,* and their *chemical composition; electricity;* the *terrestrial heat;* the *process of vitality;* and many *mechanical operations.*

§ 425.

The *rays of the sun* supply the greatest portion of the heat at the earth's surface: one convincing proof of this is, that if any body be placed in the rays of this luminary, its temperature rises. The degree in which its temperature is elevated depends on the angle at which the sun's beams impinge on its surface, on the quantity of light united in one point, on its colour, and on the absorptive power of the body itself.

A body becomes heated the more intensely by the sun's rays the nearer the angle under which those rays fall upon its surface approximates to a right angle, on attaining which the maximum effect is produced: hence the intensity of heat imparted to a body corresponds with the intensity of its illumination. (§ 285.)

Hence we understand why the sun has greater power at noon than in the morning or evening of the day; also, why snow on the roofs of houses inclined towards the south is melted before that which lies horizontally upon the ground. In like manner, we can account, from the inclination of the earth's axis towards the sun in its orbit, for the high and nearly uniform temperature of the regions near the equator; the lower temperature and the variations in the climate of those parts nearer to the poles; as well as the warmth of summer and the cold of winter generally. These results are obviously affected by the length of time the light of the sun has been in operation; for we do not experience the greatest degree of heat exactly at noon, but a little after that time; so too the hottest part of the year is not when the sun is at the solstice, but a little after the longest day.

By means of the reflection and refraction of the sun's beams they may be so combined in a focus as to produce a heat sufficiently intense to melt or convert into vapour almost all known substances. On this fact depends the operation of burning lenses and mirrors, hence also they derive their appellation. (§ 311.)

It will suffice to mention the famous burning mirrors constructed by Archimedes, also the burning mirrors and glasses of Tschirnhausen and Buffon. Parker, of London, constructed a burning glass 3 feet in diameter, and having nearly 7 feet focal distance, which fused platina, nickel, iron, emerald, asbestos, and other incombustible substances.

One remarkable property of solar light, with regard to its power of exciting heat, is that this property seems intimately connected with its refrangibility; so we see the greatest thermal intensity in the neighbourhood of the red rays of the spectrum, on both sides of which its heating power diminishes. This peculiarity has been already noticed in the section on light (§ 351.), and in that part of this work where radiant heat has been treated of (§ 388.); for further particulars, therefore, the reader is referred back to those portions of the work.

The more transparent any body is and the better it reflects light, the less does it become heated by the sun's rays; and conversely, the greater its opacity and the rougher is surface, the more intense the heat that can be excited. The colours of bodies greatly affect the readiness with which they may be heated, the bright colours having the smallest susceptibility for heat, the darker colours a greater, but black the greatest; white has the least of all.

This is so well known a property of solar light that it will suffice to adduce but one or two examples.

Our atmosphere, the most transparent substance with which we are acquainted, is the least heated by the sun's rays; glass is more so, and that in precisely the same degree in which it is inferior in transparency.

Polished metallic surfaces if exposed to the sun's rays, are always at a lower temperature than such as are rough.

Franklin's experiment, with pieces of cloth of different colours, is a good illustration of the influence of colour on a body's susceptibility of heat. Lay several pieces of cloth of different colours on the top of some snow on which the sun is shining; after a little time the darkest coloured cloth will be found to have sunk lowest beneath the surface. — Hence we see why black clothing is hotter wear in summer than similar articles of dress of lighter colour. — Paint a box black inside, close it at top with a pane of glass, and expose it to the sun's rays, the heat in the inside of the box will exceed that of boiling water.

The influence both of colour and surface, as also of transparency, with regard to heat, will be most readily seen by using a differential thermometer in the manner described in the second experiment in § 385.

Other sources of light present to us analogous phenomena only in a lower degree, as has been proved by modern researches on radiant heat. (§ 387. and § 388.) Whether heat or the excitation of heat is an essential property of every kind of light or no, has not yet been positively ascertained; but that light can retain all its luminous properties though deprived of all heating power, we see in the case of moonlight. Melloni has proved that the solar light may be deprived of its thermal properties by passing it through a sufficiently dense stratum of water.

From the facts above noticed, it has been satisfactorily established, that light in general, and especially that of the sun, is one of the principal sources of heat. As yet no perfectly satisfactory explanation has been given of the connection between heat and light: this would require such an intimate acquaintance with the nature of both as it is plain we do not possess from the mere fact, that two antagonist theories still divide the scientific world as to the nature of both light and heat.

§ 426.

One process is continually in operation on our earth by which heat is generated, namely, the *changes of aggregation* bodies undergo, the *changes in their capacity for heat*, and their *chemical combination* and *decomposition*.

It has been explained in § 399. that, when a gaseous body becomes liquid, or a liquid becomes solid, precisely the same quantity of heat is liberated as was held in a latent condition under its former state. The converse obtains when the opposite transformation happens.

So, also, heat is liberated if a body's capacity for heat is diminished. (§ 398.) This occurs whenever a body is rendered more dense by external pressure, or when its capacity is affected by chemical influence. The converse takes place when these circumstances are reversed. (See *experiments*, § 398.) The liberation or absorption of heat will be accelerated in proportion to the rapidity with which the condensation or rarefaction of the substance takes place. Those metals which admit of the greatest compression, as for example copper, give out the greatest quantity of latent heat when subjected to pressure. As non-elastic fluids are incompressible (§ 144.), the quantity of latent heat they contain is extremely small; gases, on the contrary, evolve much caloric when their volume is diminished.

Chemical changes are invariably accompanied by a change in the capacity of substances for heat: this happens because either the volumes of the bodies are altered, or they assume a new form of aggregation, or the compound has a different capacity for heat from that of its elements. Whenever chemical combination condenses a body, as when it converts a liquid into a solid, or a gas into a liquid, or whenever it lessens the thermal capacity of the newly formed compound, caloric is set free. The development of heat in detonating substances (§ 77) forms an exception to this general law; as for instance in the case of gunpowder, where the liberation of heat may be explained if we attribute it to electrical agency, which greatly modifies chemical operations. The process by which we develop the most intense heat is known as *combustion.* A general explanation of the theory of combustion has been already given in § 77.; minute details belong rather to the province of chemistry; we shall now merely adduce a few experimental illustrations of the above remarks.

1.) The term *pyrophorus* is given to such substances as, by the absorption and condensation of the aqueous vapour and other gases contained in the atmosphere, become heated and ignite.

Expt. Spongy platinum is a well-known pyrophorous body; it absorbs hydrogen and oxygen so readily, when it comes in contact with these gases, and then condenses them, that its entire mass becomes red-hot, and the gas is ignited.

This phenomenon may be excited by conducting a stream of hydrogen from a blow-pipe, or even from a common bladder, filled with the gas, upon a small piece of spongy platinum laid on a watch-glass. This property of platinum is made use of in hydrogen fireworks.

The residuum of gunpowder not unfrequently ignites spontaneously, becoming incandescent, by absorbing the aqueous vapour of the atmosphere; if breathed on, the same effect follows. Döbereiner has artificially made the compound by exposing to a red heat a mixture of one part of burnt alum, 1½ parts of carbonate of potassium, and from ½ a part to a part of smoke of deal wood. Analogous to this is the spontaneous combustion of coal, damp hay, or straw, oiled cotton, &c.; all articles of this nature should, consequently, be carefully stowed away.

2.) Another example of the same kind is afforded in the heat generated by throwing water on quicklime. The development of heat is accounted for by the formation of a hydrate of lime, in which the water assumes the solid form.

3.) A mixture of water or ice with sulphuric acid produces a high degree of heat.

§ 427.

Electricity is one of the most powerful agents by which heat is produced: of this we shall, however, speak at greater length in that part of this work which is especially devoted to that branch of physical science, when it will be made evident that electricity affects the most diverse processes of nature.

§ 428.

The *terrestrial heat* is the source to which the internal solid mass of our earth is indebted for its warmth. Modern research has placed it beyond all doubt, that the temperature of the earth increases the lower we descend below its surface. Experiments have been undertaken, chiefly in artesian wells and mines, the object of which has been to measure, at different places, the increase in this temperature.

Professor Reich of Freyberg, Marcet, De la Rive, Erman, and Magnus have conducted experiments of this kind. The instrument best adapted to this purpose is the *Geothermometer*, invented by Magnus. Although these researches have not yet enabled philosophers to ascertain the law for the increment in the heat, yet, taking the results at a mean, it would seem that the temperature rises 1° Fahr. for every 60 or 70 feet we descend below the surface; hence, at a depth of a few miles, the earth must be in a state of incandescence.

This heat is not the effect of the sun's rays, but is owing to some internal source. That such an internal terrestrial heat does actually exist we have pretty good reason for believing, for how else can we account for the many hot-springs which gush up from great depths below the earth's crust? How could the earth have acquired its flattened form at the poles, had it not begun to revolve when its mass was in a soft, if not actually in a fluid, state? (§ 47.) If, now, we suppose that this fluid condition was owing to the action of heat, and that our planet was once in a state of fusion, then, as the process of solidification was carried on, heat would be continually liberated, and this emission of caloric might last for centuries.

This heat is not to be confounded with the *superficial* warmth or temperature of the earth's surface, which depends principally on the action of the sun's rays, and which decreases (for reasons already explained in § 425.) as the latitude of places increases; a warmth which varies with the time of day and year, which is greater in the northern and eastern hemispheres than in the southern and western, which is regulated by the nature of the soil, and by its elevation above the level of the sea. The temperature at the surface is subject to the greatest variations; the daily variations extend to a depth of about 1¼ feet, the monthly to about 3 feet, and the annual to some 30 feet.

Our atmosphere derives a portion of its warmth from the sun's rays which pass through it, but its principal source of heat is the radiation that is going on from the surface of our planet. It varies, therefore, with the climate and latitude of a place, and near the surface of the earth it corresponds with that of the earth itself; as the height of the strata increases, their temperature decreases. No fixed law has yet been discovered by which the decrease of temperature is governed. From a mean of numerous observations made by Saussure, Pictet, D'Aubuisson, Von Zach, Horner, Ramond, Von Humboldt, Playfair, and Atkinson it has been found, that the temperature falls 1° Fahr. for every 290 feet we ascend above the level of the sea.

The *mean temperature* for any place can be obtained only from a large number of observations, on account of the frequent changes in the warmth both of the atmosphere and of the earth's surface. The temperature of the air is generally taken at a height of from 5 to 10 feet above the ground. The *mean daily temperature* is got by taking the average of four observations, viz. at 4 and 10 A.M. and P.M.; the *mean monthly temperature*, in like manner, is the arithmetical mean of the daily temperatures for a month; and the *mean annual temperature* is the mean of the monthly temperatures; or it may be found with sufficient accuracy by taking the mean of the temperatures for April and October. So, also, a pretty correct approximation for the mean daily temperature is got from the points of maximum elevation and depression, as shown by a self-registering thermometer. (§ 268.) Repeated observations have proved, that the mean temperature of any place gives the warmth of the ground 30 feet below the surface.

Connect, by a line, all those places on the surface of the globe which have the same mean temperature, and you have what is called an *isothermal line*. If the thermal relations depended solely on the operations of the sun's beams, these lines would be parallel to the equator, and the temperatures themselves would be proportional to the square of the cosine, of the latitude. This is, however, by no means the case, and consequently, the isothermal lines form curves, deviating widely from concentric circles. In general, in Europe, they incline most to the north; whence, under equal latitudes, this continent is warmer than America and Asia. The *isothermic maps*, first drawn by A. von Humboldt, show at a glance the limits of equal temperatures all over the world.

§ 429.

The *process of animation*, or the *vital principle*, which is so intimately connected with the existence and life of all organic bodies, is also one of the principal sources of heat. It is a well-known fact, that living animals have in themselves a source of heat, and that their temperature is almost independent of that of the ambient fluid.

The temperature of the human body, in a healthy state, stands pretty steadily at from 97° to 99°, independently of the rise or fall of the external heat. The temperature of many animals, as, *ex. gr.*, that of birds, is higher, generally 100°.

The temperature seems to stand at this uniform elevation, in consequence of the various functions of vitality, the development of heat being caused by the chemical combinations and decompositions attendant on the process of respiration, and by the purely electrical action, which, in all probability, accompanies the operations of the nervous system.

Even vegetable life is a constant source of heat, though less high and less uniform than animal life.

§ 430.

Lastly; the *mechanical means* by which bodies are heated, or by which latent heat is set free, consist principally in the operations which are brought about in bodies by *pressure*, *percussion*, or *friction*.

In the first two modes heat is liberated in consequence of the body's density being increased, and its capacity for heat being thereby lessened. (§ 393.) When external pressure can no longer reduce the volume of any body, its temperature will not rise. The excitation of heat by friction does not admit of so ready an explanation, for it appears to depend on some peculiarities in the nature of heat, with which we are still unacquainted.

The following may be named as instances of heat excited and liberated by mechanical means:—All solids, but especially the metals, may be heated by striking. A bar of iron may be made red-hot merely by hammering it. In the year 1834 some experiments were performed at Metz, to determine the effects of cannon balls discharged against masonry. It was found that the balls, as they sank into the limestone, of which the wall was composed, generated so strong a heat, that the surrounding stone seemed to have been burnt, and the balls themselves, for some hours, retained a sufficient degree of heat to burn any person who touched them.

Gases, by virtue of their extreme compressibility, may be considerably heated, and the degree in which their temperature is raised may even be calculated accordingly. (§ 396.) An illustration was given in the *first experiment* § 398. of combustion produced by a great compression of the air.

The combustion of different detonating salts and powders on being struck or even pressed.

The striking a light by means of a flint and steel.

Steel tools, such as gimlets, saws, files, &c., become hot when used.—Fire procured by savages rubbing together two sticks.—Friction is also the cause of the axles of carriages, the cranks of large machines, the sockets in which the axles of fly-wheels work, and the cords that pass over pulleys, becoming intensely heated, and sometimes firing. This effect of the friction is checked by applying some unguent to the axles and cranks of machinery, and moistening cords and wooden wheels.—The borers by which cannon are bored become so hot that they would blister the hands if touched.

IX. CONCLUSIONS RESPECTING THE NATURE OF BOTH LIGHT AND HEAT.

§ 431.

In the early part of this chapter (§ 362.) we just glanced at the opposite theories which have been entertained respecting the nature of heat; now having noticed some of the principal phenomena, we shall be better able to compare these theories, and observe how far the explanations they afford are satisfactory; at the same time we shall have an opportunity for remarking the striking analogies subsisting between light and heat.

According to the older hypothesis these different phenomena were attributed to a material substance of heat, which closely resembled the matter of light, but which was supposed not to be identical with it. This material heat was imagined to be a very fine, highly elastic fluid, but destitute of the primitive properties of all other matter, such as weight, impenetrability, &c. All bodies, whatever, were supposed to contain this hypothetical heat in certain but unequal proportions, and especially substances were conceived to have for it a different and varying attractive force. Most of the phenomena that come under our notice may be satisfactorily accounted for on this hypothesis, but not all, as *ex. gr.* the fact, that radiation goes on at all temperatures; for it is an established fact, that heat radiates even from such bodies as have a lower temperature than the others by which they are surrounded. Again; the uninterrupted development. of heat by friction and electricity are not satisfactorily accounted for on the corpuscular theory. Lastly; the great similarity subsisting between light and heat does not admit of so satisfactory an explanation as upon the undulatory hypothesis.

According to the second theory, which has been very extensively adopted, light and heat are really identical powers, which display themselves in different modes of operation, and which are convertible the one into the other. On this assumption heat would appear to us as light, if its motion were altogether free ; but if the light were deprived of its free and rapid motion by the operation of other bodies, then we should recognize the same agent at work as heat. The phenomena which bear out this hypothesis are the following, viz. that light produces heat, not merely by concentrating it but also by preventing its radiation, in which case it will be absorbed by bodies. (§ 385.) All substances become luminous when their heat reaches a certain point, varying with the nature of the particular substance. Radiant heat in its motion obeys precisely the same laws with light (§ 380—389.), and probably would appear as light to an eye of greater delicacy than ours. Although this theory assumes that luminous phenomena are never to be found uncombined with those of heat, and that the latter are joined with them either as cause or effect, yet this assumption is not borne out by experience.

The third hypothesis. which steadily gains an increasing number of adherents, is compounded of the two preceding theories. It assumes the existence of an æther which serves as the substratum for the joint phenomena of both light and heat, which owe their origin to the vibratory movements of this imaginary fluid, exhibiting to us the phenomena of heat or light, according to the less or greater velocity with which the particles are set in motion. (§ 381. and 389.)

Professor Baumgartner expresses himself in the following manner: — If the phenomena of heat be compared with those of light and sound, we cannot fail to be struck with the great resemblance between them. Light and heat generally exist simultaneously in the same body; they are subject to the same variations, and obey the same laws; both are propagated in right lines, in vacuo, and in air of uniform density; both travel with incredible velocity; both are refracted, dispersed, reflected, polarized, absorbed, &c, for the most part according to the same laws. With regard to sound, it has been proved, that it is caused by the vibrations of the particles of bodies. Now, between heat and sound many points of coincidence have been found; for example, both are excited by means of friction, both are propagated by radiation, both suffer reflection, and both lose in intensity by passing from one medium to another. As the rays of sound render a body sonorous, so those of heat render it warm: whilst a body sounds in harmony with the original note, the sound is also propagated; thus, as any body becomes heated by another, it also imparts heat to whatever surrounds it. Now, it has been proved beyond dispute, that sound is essentially owing to the vibrations of bodies, and as its radiant propagation can be conceived of only as the result of undulatory movements, for no fluid has yet been discovered whose parts radiate (*i.e.* advance in right lines), analogy requires us to assume that heat, like sound and light, consists essentially in a vibratory motion; the vibrations of sound taking place in the particles of sonorous bodies, whilst the undulations of light and heat transpire in æther. The luminous vibrations have a greater velocity than those of heat, the former exciting in the optic nerve the sensation of light, much as the vibrations of sonorous bodies produce in the organs of hearing the sensation of sound. The more tardy vibrations of the æther cause merely the sensation of heat or cold in this respect resembling those vibrations of a sonorous body, which are perceptible by the sight and touch, though not sufficiently rapid to produce a sound. The supporters of the views just developed are not agreed as to whether the phenomena of heat are owing solely to the vibrations of the æther, or to those of the bodies themselves, or in part to both.

A curious phenomenon, and one which is favourable to this theory is, the emission of sounds by heated metals when placed under advantageous circumstances. The most convenient apparatus for their production is the *Thermophon*, called also, after its inventor, *Trevelyan's Instrument*. It consists of a metallic body, generally of brass, which is first heated and then laid on a cold block of lead, to which it gradually imparts its heat; during the process of cooling, the former body contracts in a manner by regular pulsations, and in so doing emits musical sounds, which cease entirely when the temperatures of the two metals are equalized.

If now we review the various phenomena of light and heat, we shall find many things which cannot be satisfactorily accounted for upon any one of the theories we have noticed. Hence we must admit that, in our present state of knowledge, the nature of heat and light is not so thoroughly understood as to warrant us in pronouncing unhesitatingly as to the accuracy of this or that view; and lastly, in the construction of theories, it behoves us to proceed with greater caution than was exercised by men of science in bygone times, the very much wider range of phenomena brought under our view rendering it more difficult satisfactorily to explain them according to any single hypothesis, than it was for our predecessors to account for the comparatively small number of phenomena on which their theories were built.

SECTION III.

MAGNETISM.

I. PHENOMENA OF MAGNETISM IN GENERAL.

§ 432.

In the preceding sections in which we have treated of the phenomena of light and heat, we found that the senses of sight and touch were affected by these two agents respectively. *Magnetism*, which we have next to consider, differs essentially from them in this respect, that it exerts *no* immediate influence whatever on *any part of our nervous system.* Substances endowed with magnetism *attract certain metals; they display towards one another a force partly attractive and partly repulsive;* and lastly, *they exhibit a tendency to arrange their mass in a certain direction.*

However simple these isolated fundamental effects may appear, yet the ultimate causes which produce them must remain shrouded in obscurity, unless we can discover the laws which regulate the mutual operations of this and the other physical agents on each other. Our knowledge of this subject has been greatly increased of late by the discovery of electro-magnetism and magneto-electricity (which are treated of in the concluding sections of this work); and the fact has been established beyond dispute, that magnetic influences are affected by, and that they in their turn affect, heat, light, and electricity. We may, therefore, well hazard a conjecture, that magnetism has a far wider sphere of operation than the exertion of its attractive and repulsive forces would indicate; and that, probably, many a phenomenon is ultimately owing to magnetic influence, although the mode of its connexion with that force is unknown to us.

The existence of a magnetic power was known from an early date; but the ancients were acquainted only with the attractive properties of the loadstone, to which mineral they gave the name of *magnet*, probably from the circumstance of its being found in abundance in the neighbourhood of Magnesia, a city of Lydia, in Asia Minor. The method of making artificial magnets was discovered in the 14th century, and the science soon acquired increased importance on the introduction of the mariner's compass into Europe. The rapid advances which have since been made in every department of natural science have caused the laws of magnetic influence to be more closely studied; our acquaintance with the operations of this powerful and widely extended force has accordingly become much enlarged.

II. NATURAL AND ARTIFICIAL MAGNETS.

§ 433.

Such bodies as possess the attractive power we have described above, are termed *Magnets;* they are known by their drawing towards themselves, though from different distances, iron, steel, nickel, and cobalt, as also such other mineral substances as contain a portion of iron in their composition. If the attraction be converted into absolute contact, the magnet will hold the other body with a force whose intensity depends on a variety of circumstances. If a magnet be placed so that it can move its mass freely, it will invariably assume a certain definite position with respect to the earth.

Magnets are either *natural* or *artificial:* the former are iron ores, often called *loadstones*, and are found either at or below the surface of the earth; the latter are commonly of steel, they are of various forms, and the magnetic properties are imparted to them by a process which will be described presently; they are named according to their shape and the manner of their combination. Those artificial magnets, which are constructed so as to move freely, and which will therefore take the certain determinate position already spoken of, are called *needles:* of the different varieties we shall speak particularly by and by.

The loadstone is a chemical combination of the oxide and suboxide of iron ($Fe.O$, $Fe.O_3$). It is found pretty extensively distributed, especially in the northern parts of the world, N. America, Norway, Siberia, &c. In many of these regions the mineral exists in such abundance as to form whole mountains, and, if regarded as a single magnet, must be one of prodigious power. Repeated experiments have, however, led to the belief, that the interior strata of this mineral do not possess any magnetic properties, but that its influence is limited to those portions which are exposed to the air.

We have already observed that artificial magnets are of various forms; if they be either cylinders, or parallelopipeds, they are called *bar magnets*; if curved in the middle, so as to bring the two ends near together, they form *horse-shoe magnets*; when several bars or horse-shoes are combined, the whole is called a *compound magnet*, or a *magnetic battery*; and sometimes, more simply, a *bundle* of magnets.

§ 434.

Both the magnet and the body it attracts exert a reciprocal influence on each other; that is to say, the magnet attracts the iron or other substance, which in its turn attracts the magnet.*

The following experiments will illustrate this fact: —

First Expt. Suspend a piece of fine iron wire by a thread, so that it may hang horizontally. — Present a powerful magnet to one end of the wire, and the attractive force of the former will at once be evident.

Second Expt. Suspend a magnetic needle in like manner; offer to it a large piece of iron, and the needle will follow the iron in this case as the wire did the magnet in the former.

§ 435.

Magnetic attraction will be transmitted unimpaired through both solid and liquid bodies, and through gases either rare or dense; iron and such other substances as are capable of being magnetized, form the only exceptions to this rule.

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* NOTE. — Perhaps it would be more correct to say, that "the attraction, which is *apparently* between the magnet and a piece of iron, is *actually* between two magnets presenting to each other opposite poles." — Walker's Magnetism, p. 394. in Lardner's Cab. Cyclop. See also § 439. in this work.

First Expt. This may be easily shown by interposing between the magnet and the other bodies described in the experiments under the preceding section a screen, of any substance whatever, as glass, wood, metal (excepting only plates of steel and iron), or a flask containing any liquid or gas.

Second Expt. Strew some iron-filings on any flat surface, place a magnet beneath, and the filings will readily follow in whatever direction the magnet is moved.

Third Expt. Interpose an iron plate between a magnet and a piece of iron wire suspended by a thread, the influence of the magnet will be almost or entirely destroyed.

§ 436.

This attractive force does not exist with equal intensity at all points of a magnet's surface; generally it is found to be most powerful at two points only, whilst at others it is either exerted but feebly, or it ceases altogether. These two points are termed the *poles* of the magnet, and the right line joining them is the *axis.*

The poles may be readily found by their more powerfully attracting iron-filings, or if the magnet be allowed to move freely when it comes to a state of rest, it will arrange itself north and south in such a manner that its axis will pretty nearly coincide with the geographical meridian. When the needle has assumed this position, that end which is nearest to the north pole of our earth is called the *north pole* of the magnet, and the opposite one is termed the *south pole.* *Anomalous magnets* are such as have more than two poles.

First Expt. Sprinkle some iron-filings on either a natural or on an artificial magnet; a considerable number of the particles of iron will attach themselves to the poles, whilst the other portions of the magnet will be left nearly bare.

This furnishes us with a ready method of detecting the poles of a natural magnet. Now, if the two poles of the magnet be polished and covered over with smooth plates of iron, which terminate in two strong projecting ends, such a magnet is said to be armed. The magnetic power, imparted by this means to the two iron plates, is concentrated in the knobs, and thus a north and south pole are made.

Second Expt. Place either a natural or an artificial magnet in such a situation that it can move itself freely in a horizontal direction; this will be best effected by suspending it; and it will soon be seen that the axis will assume the polar position spoken of above.

§ 437.

On more closely watching the operations of this magnetic influence, we shall find both the poles attract those substances named in § 433.; but that if two magnets be presented to each other they may either attract or repel according to the poles which are offered; that is to say, if a north pole of one magnet be presented to the south pole of another, attraction will ensue, but if a north pole be presented to a north pole, or a south pole to a south pole, the magnets will repel each other. This law is thus expressed: *like poles repel and unlike attract.*

If the similar poles of two magnets be brought into absolute contact, the magnets will exhibit either a feeble attraction for each other, or none at all, according as the influence of the two poles is in part or altogether cancelled. To represent these opposite magnetic influences, that of the north pole is called *positive magnetism*, or + M, and that of the south pole *negative magnetism*, or — M.

First Expt. Both ends of an iron wire, moving freely in a horizontal plane, are attracted equally by the north and south poles of a magnet.

Second Expt. If a magnetized needle be allowed to move freely in a horizontal direction, and a magnet be presented to it, we shall find that the dissimilar pole will invariably attract, and the like pole repel the needle. — The same result will follow if a common sewing needle be magnetized and suspended by a thread passing through its eye, and the north and south poles of another magnet be successively presented to it.

Third Expt. Attach a bar-magnet to one arm of a balance in such a manner that its axis may be vertical to the horizon; then place a counterpoise at the other extremity of the beam. — Place a second magnet immediately beneath the vertical one, first, so that like poles shall be together and then unlike. In the former case the arm of the balance which carries the magnet will rise, in the latter it will descend, being drawn down by the magnetic attraction.

Fourth Expt. Hang a piece of iron, as a key to the north pole of a magnet, and present to it the south pole of an equally powerful magnet. The key will instantly fall, for + M and — M neutralize each other's effects.

Fifth Expt. Plunge the poles of two magnets into some iron-filings. Bring together like poles of each, and most of the filings will drop; but present unlike poles, and the filings will move towards each other and at length join.

If we investigate still further the attractive force of a magnet along the entire course of its axis, we shall find that this power continually diminishes the farther we proceed from either pole, until we reach a point somewhere about midway between the two extremities, where it ceases altogether. This spot is termed the *point* or *line of magnetic indifference.*

This decrease in the attractive force of a magnet may be readily seen by strewing iron-filings upon it. The following experiment will show how to discover the situation of this point of indifference, the gradual decrease in the attracting power, and the change from + M to — M.

Sixth Expt. File away the bottom of a common medicine vial, suspend a small magnetized needle inside the vial, so that when the former is placed on a bar-magnet the needle may hang in a horizontal position at about an inch from the bottom of the vial; when the needle is over the north pole of the bar its south pole will be drawn downwards. As the apparatus is pushed along, this attraction diminishes until somewhere about the middle the needle hangs perfectly horizontally, it must then be above the line of indifference; as it is moved beyond this place, the north pole of the needle becomes more and more depressed the nearer it approaches the south pole of the magnet.

Lastly; if a magnet be broken anywhere in the direction of its axis, each part becomes a perfect magnet, whose poles lie in the same direction with those of the whole magnet, so that at the line of fracture the opposite species of magnetism has been excited.

Seventh Expt. Break a magnetized knitting-needle into several pieces, test the polarity of each end, and the truth of the above remark will appear.

§ 438.

If iron or any other substance, susceptible of magnetic influence, be brought into contact with the pole of a magnet, then such body will also be magnetized, and throughout its mass it will possess the magnetism of the pole with which it is in contact.

First Expt. Place a short piece of soft iron, or a key, in contact with the north pole of a powerful magnet; the entire mass of iron will acquire north polar magnetism, for the south pole of a magnetic needle will be attracted by any part of the iron to which it may be offered.

Second Expt. Procure several small pieces of iron wire and offer the end of one to the pole of a powerful magnet; it will be immediately taken up by it, and the free end of the wire will now attract and support a second wire, this again will carry a third, and so on till the weight of the metal exceeds the attractive force.

The same phenomenon may be observed with regard to iron-filings adhering to a magnet; each individual filing thus suspended is converted into a small magnet, which attracts and magnetizes a second, third, and so on. This enables us to account for the falling off of the filings from the end of the magnet, as described in the fifth experiment of the preceding paragraph, when a like pole was presented to that to which they were adhering.

Third Expt. Sprinkle some iron-filings thinly on a pane of glass or upon a slate, place a magnet underneath, shake the glass a few times with the edge of the magnet, or the magnet and the plane may both be at rest, and the filings may then be gently let fall on the surface of the latter. Whichever arrangement may be adopted, the filings will be found to accumulate themselves most perceptibly about the poles of the magnet, and to arrange themselves so as to form curved lines extending from one pole to the other. This phenomenon may be thus explained: each individual filing becomes a magnet; dissimilar poles therefore attract, and so form continuous rows of magnets from one pole of the magnet which is beneath the glass to the other, or, at least, they exhibit a tendency to do so. The lines thus formed are named the *magnetic curves.*

Pure soft iron receives the magnetic influence most quickly and easily, but it also parts with it in the shortest time, when separated from the magnet. Hardened steel and cast iron, especially in large masses, are not so soon magnetized, but they retain the magnetic properties imparted to them by the magnet for a longer period on being detached from it. A piece of steel thus magnetized acquires polarity also; that is to say, if it has been in contact with the north pole of the magnet, then that extremity of it will be a south pole, and the opposite end will be a north pole; if it has been in contact with the south pole of the magnet, these circumstances will be reversed. No other metals besides nickel and cobalt become magnetized by contact with a magnet.

§ 439.

Every pole (+ M or — M) excites magnetism in any magnetizable body within a certain distance of itself, imparting an opposite polarity to its own to the contiguous end of such a body, and similar polarity to its remote end. Bodies in this state are said to be *magnetized by induction,* and the range within which the magnet exerts an influence is termed its *circle of magnetic influence*, or its *magnetic atmosphere.* This influence may be either transient or permanent, as it is induced in pure iron, or in iron containing a portion of carbon. — In this condition of induced magnetism the general law of magnetic attraction begins to operate (§ 437.), and the magnet and the other body exhibit a tendency to approach; whence we may infer that every case of magnetic attraction is owing to induction; thus, *ex gr.*, a piece of soft iron is itself converted into a magnet before it can be attracted towards a magnet.

The following experiments will illustrate magnetism by induction: —

First Expt. Suspend two small pieces of soft iron wire by a thread in such a manner that they may hang vertically side by side, and near to each other, as shown in *fig.* 129. by the lines *n s.* Now bring the pole of a powerful magnet close to the lower ends of the wires, and we shall see, 1.) that both the upper and lower extremities of the wires repel each other, and so bring the threads out of the perpendicular; and 2.) that the lower ends of the wires show a tendency to approach and touch the magnet presented to them. This phenomenon can however only be brought about when the lower ends of the wires have acquired an opposite polarity to that of the magnet offered to them, whilst the upper ends have a like polarity with it: this is shown in the figure.

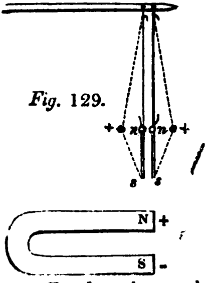
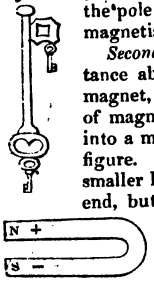


Fig. 129.

Substitute for the iron wire two common needles; these will be rendered permanently magnetic, their points having an opposite magnetism to that of the pole presented to them and their eyes the same magnetism with it.

Second Expt. Hold a large key at some distance above one pole of a powerful horse-shoe magnet, as represented in *fig.* 130., and by the laws of magnetic induction it will itself be converted into a magnet, having its poles as shown in the figure. Under these circumstances, it will carry a smaller key at its upper and another at its lower end, but if it be moved in either direction sideways, it will soon arrive at a point beyond the influence of the magnet, when the small keys will fall off.

Fig. 130.



§ 440.

We have already remarked that (§ 433.) magnets exert their attractive influence at various distances from bodies susceptible of it; that the intensity of this force consequently is not uniform, but that it varies with the distance.

Expt. This may be easily shown by bringing a magnet near to a magnetized needle; the deviation of the latter is perceptibly greater the nearer the magnet is brought to it; it diminishes as the magnet is removed to a distance.

By experiments, which will be described and explained hereafter, it has been ascertained that the intensity of magnetic influence diminishes in the same ratio as that of all forces acting from a centre, viz. as the squares of the distances; so that, if the distance be increased two, three, four, *n* times, the attractive force will be one-fourth, one-ninth, one-sixteenth, $\frac{1}{n^2}$ of what it is at the distance assumed as the unit.

§ 441.

As the nature of magnetism is as yet undiscovered, we are obliged to have recourse to hypothetical explanations when we account for the various magnetic phenomena: on this subject philosophers are of different opinions. Some suppose (as they do with regard to light and heat) that there exists an extremely subtle imponderable fluid, combined with the particles of those bodies which are susceptible of magnetic influence, perhaps indeed with the particles of all bodies. This fluid is further supposed to consist of two distinct parts, or rather of two fluids, distinguished as *north* or *positive* magnetism ($+$ M), and *south* or *negative* ($-$M); neither of which, however, is found singly combined with the particles of matter, but always both together. The particles of the same kind of magnetism display a tendency to repel each other, but the opposite kinds to attract. Now, if the relative proportions of these two fluids existing in any body be such that they mutually neutralize each other in the individual molecules composing it, no magnetism is displayed, and such a body would be said to be not magnetized. But if this condition of equilibrium be disturbed, or a separation be effected by any external cause whatever between these two fluids, then the magnetic state is induced and the magnetism is invariably *bipolar*, never *unipolar*. The attractive energy of each of the magnetic fluids may be further supposed to be accumulated in the respective poles. Every body that has acquired this state of polarity is in its turn capable of disturbing the magnetic equilibrium of other similar bodies within certain limits, separating in them these two fluids or polar forces, attracting that which is like and repelling that which is unlike itself. (Comp. § 272.) The derangement thus effected in the magnetic fluids is not sufficient to cause their passage from one particle of the body to another, still less from one body to a another. By assuming this hypothetical fluid to be thus combined with the molecules of substances, we can explain how a magnet, or any other body in a state of magnetic activity, may excite the same condition in others without any loss of its own powers; as also why, when a magnet is broken, each portion is a complete magnet having two poles.

Fig. 131.

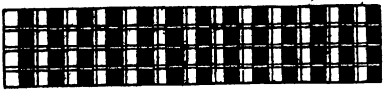


Fig. 131. may serve to give a visible representation of this supposed distribution of the antagonist forces in the interior of a magnet, the small squares representing the molecules of the magnet, each of which contains the two polar forces in their separate condition, divided so that the like are all turned in the same direction, and the one force acts at one extremity of the magnet, and the opposite force at the other end. (The antagonist forces are expressed by the black and white chequers.) Hence also it is apparent why, if a magnet be broken across, each portion will be a perfect magnet, and will have two poles. (See also the *seventh experiment*, § 437.)

This separation of the magnetic influences is not effected with equal readiness in all bodies. The more easily it is accomplished, the sooner do they again combine; or, in other words, the more quickly any body becomes magnetized, the sooner also does it lose the magnetic properties it had acquired. To account for this fact, it is assumed that different substances offer a very unequal degree of resistance to the magnetic influence, which tends to separate the two species of magnetism they contain. We need not assume that all those substances which have as yet resisted magnetic influence are therefore absolutely destitute of the magnetic principle; it will be enough if we suppose that the means hitherto used have not been sufficiently powerful to overcome their molecular resistance. According to another and more modern theory, deduced from observations on the phenomena of electro-magnetism, or the mutual action of electricity and magnetism on each other, the latter has been regarded as merely an electrical phenomenon. The reader will find the subject of electro-magnetism treated of distinctly in the concluding sections of this work, to which he is referred for a full account of this theory.

III. TERRESTRIAL MAGNETISM.

§ 442.

Since, by the law of magnetic polarity, unlike poles attract, it follows that, if a magnet be suspended freely between the dissimilar poles of a more powerful fixed magnet, the former will arrange itself, so that its north pole shall be opposite to the south pole of the latter, and its south pole opposite to the north pole of the fixed magnet; in such a manner, in fact, that the axis produced of the moveable magnet will pass through the poles of the fixed one.

> *Expt.* Suspend a small magnetized needle horizontally between the poles of a horse-shoe or bar-magnet. Whatever the position of the magnet with respect to the poles of the earth, the north pole of the needle will invariably be found to point towards the south pole of the magnet, and its south pole towards the magnet's north pole.

All magnets that have free motion in a horizontal plane in any part of our earth arrange themselves, so that one pole, called the north pole, points nearly towards the north pole of the world, and the opposite pole towards its south pole. — The inferences to be deduced from this fact will be considered presently; the fact itself is all that we assert now, viz. that a needle in any part of the earth invariably maintains a certain position as if it were placed between the two poles of a fixed magnet.

Now, if we conceive a vertical plane to be drawn through the axis of such a needle when in a state of rest, we have the *magnetic meridian* for the particular place where the needle is. There are but few points upon the earth's surface where the magnetic and geographical meridians coincide; consequently, the needle does not point due north. The angle which the former makes with the latter, at any place, is termed the *magnetic declination*, or the *variation of the needle* at that particular place. It is spoken of as either *east* or *west*, according as the needle points eastward or westward of the geographical meridian.

The magnetic needle is a highly important instrument for the natural philosopher; and to mankind in general it has proved of essential service in guiding the mariner safely over the trackless ocean. It enables the traveller in unknown regions to determine the azimuth of objects; it is used by the surveyor and by the miner; and lastly, it is employed by the mineralogist as a test of the presence of iron in minerals and ores. Of late it has been applied as a gauge of extreme delicacy of the intensity of certain electrical forces.

The simplest method of finding the magnetic meridian at any place is to suspend a needle by a piece of untwisted silk or cotton; but for many purposes it is more convenient to balance it upon a fine steel point, which is let into a small cap or cone just over the needle's centre of gravity. To diminish friction, the cap is frequently of agate.

Fig. 132.

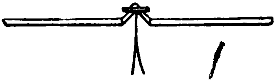


Fig. 132. presents a transverse section of a magnetic needle.

To render the variation of the needle susceptible of measurement, its point of motion is placed in the centre of a circle, which is differently divided, according to the purpose to which it is to be applied. In the *mariner's compass*, the circle traversed by the point of the needle is marked off into 32 *rhumbs* or *points*, whilst in the *azimuth compass* the same circle is divided into 360°. — If we wish to find the north and south points of the horizon accurately for any particular place by means of an azimuth compass, we ought to know the variation of the needle at that particular station, and make a proper correction for it. In some compasses this declination is expressed by a line; but, as we shall soon show, such a contrivance is of little use, as the declination is not only different at different places, but it varies from time to time at the same place. Again, for the purposes of geodesy, the compass is not to be implicitly relied on, as its accuracy may be affected by other causes, such as the proximity of strata of loadstone, basalt, &c.

The quantity of iron or other magnetic substances in minerals is found by observing how much they deflect the needle.

It is not known to whom we are indebted for the original invention of the compass. It has been asserted that the Chinese were acquainted with its use 1100 years B. C.; it was introduced into Europe in the 14th century.

§ 443.

Numerous observations made during several years have led to the conclusion, that there exist two lines on the surface of the earth on which the horizontal needle points to the true north; in other words, where the magnetic meridian coincides with the geographical. These *lines of no declination*, to which Professor August has given the designation of *agonic lines*, are two in number: one, called the *American agone*, is in the western hemisphere; the other, or *Asiatic*, is in the eastern hemisphere. They extend from south to north, but they do not coincide with the meridians; for they both, especially the Asiatic one, intersect the latter lines under different angles. It has further been ascertained, that their position is by no means stable; for, after the lapse of considerable intervals of time, it is sensibly altered. The declination of the magnetic needle gradually increases on both sides of the agonic lines, and somewhere about midway between the two it attains its maximum declination in both the northern and southern hemispheres. In those regions of the earth which lie west of the Asiatic agone towards the American, the declination is west of the north; in the other parts of the earth it is east. If those places which have an equal declination west or east be connected by lines, we have the *isogonic lines*, or *lines of equal declination*. Some of these form curves inclosing a space, whilst others branch off both north and south; most of them, however, are drawn around two points near to the north and south poles of our planet. These points, of which, until lately, it was thought there were two pairs, are called the *magnetic poles of the earth*, or, as Hansteen more correctly termed them, *magnetic points of convergence*.

Several philosophers have constructed maps, in which we are presented at a glance with the distribution and relative position of these lines on the earth's surface; the principal are those drawn by Hansteen, Barlow, Ermann, jun., Duperrey, Gauss, and Weber. Now if we inspect maps of this kind, constructed at different periods, we shall be able to see at once the changes which have taken place in the position of these lines. According to the most recent researches of Gauss, it is thought there is a greater and a lesser agone, the former embracing the globe like a meridian passing through the magnetic pole, and dividing the earth into two hemispheres, the eastern parts of N. and S. America being comprised in the western hemisphere, and New Holland, Arabia, Persia, and Russia in the eastern. The lesser agone forms an oval, and runs through Eastern Siberia, China, and the neighbouring sea.

Hence isogonic lines of western declination will be found in Europe, Africa, and the south-western parts of Asia; also in the whole of the Chinese empire, the Atlantic Ocean, and the Indian Sea. Similar lines of eastern declination are found in the greater portion of N. America, and in nearly the whole of S. America, the eastern half of Australia, India within and without the Ganges, the greater part of Siberia, and the whole of the Pacific Ocean. The mean declination in Europe is 17°; it increases towards the west (at Bonn it is 20°, at Edinburgh 26°, in Iceland 38°, and in Greenland 50°); it decreases towards the east (at Königsberg it is 13°, and at Petersburg 6°).

On the position of the magnetic poles or convergence points, more will be said in the observations, § 446.

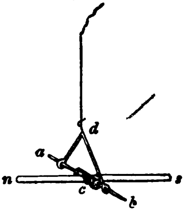
§ 444.

If a magnet, suspended horizontally, have free motion about an axis only in the vertical plane, then it follows by the laws of magnetic attraction, that if we place another magnet beneath it, its poles will be drawn downwards towards the contrary poles of the lower magnet. Needles which are perfectly free about their centre of gravity, but which have motion only in a vertical plane, are termed *dipping needles*.

If a dipping needle be placed over the axis of a magnet and between its poles, then they will both exert an attractive and repulsive influence on the needle; if their forces be exactly equal, which will happen if the needle be at an equal distance from each extremity of the magnet, the needle being acted on by two equal forces in opposite directions, will obey the laws of gravity, and arrange itself in a perfectly horizontal position. But if the needle be nearer to one of the poles of the magnet than to the other, it will be more powerfully solicited by the former, and that in precisely the proportion in which it is nearer to it. The influence of the more remote pole will be altogether annihilated, when the needle's centre of gravity is brought perpendicularly over the other pole. One effect of this is, that the needle loses its horizontal position, and that pole begins to dip which is moved towards the contrary pole of the magnet, its depression constantly increasing, until at last the needle assumes a vertical position. Next, if the dipping needle be placed so that the plane of its motion be at right angles to the axis of the magnet, it will lie perfectly horizontal when immediately above the magnet's point of indifference, *i. e.* midway between its extremities; but if the needle be moved towards either of the poles of the magnet, it is obvious that it becomes subjected to the magnetic influence of only that one pole; it will, therefore, assume the vertical position.

The above remarks may be readily verified, by placing a dipping needle in the positions just named with respect to a bar-magnet laid horizontally beneath it. — Professor Schmidt gives the following method of preparing a dipping needle that may be used by such persons as do not possess a more accurate instrument. — Thrust a magnetized knitting

Fig. 133.

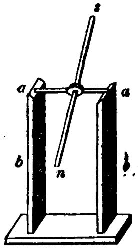


needle (*fig.* 133. *n s*) through a cork *c*; furnish the latter with an axis, consisting of two needles, *a* and *b*, at right angles to the magnetized needle. Let the direction of this axis go as nearly as possible through the centre of gravity of the whole mass. Suspend this instrument by a piece of wire, *a c d*, and fasten the whole to an untwisted silk or cotton thread. The needle *n s* is to be thrust so far into the cork that it may balance.

If an unmagnetized needle be suspended by its centre of gravity, and it be free to turn in a vertical plane (see *fig.* 133.), it will balance itself in a horizontal line. But if the needle be magnetized and placed with its plane of motion in the magnetic meridian, we shall find it has lost its horizontal position; that in the northern hemisphere its north pole and in the southern hemisphere its south pole become depressed; and that it assumes one certain position, to which it invariably returns on being displaced. If the needle's plane of motion be at right angles to the magnetic meridian, the needle becomes vertical.

Second Expt. This phenomenon may be most simply illustrated in the following manner: — Drill a hole in the middle of a piece of watch-spring, pass a needle through the hole, so that the watch-spring may be turned round in a vertical plane, and, come into a horizontal position, when in a state of rest. — Now magnetize the needle and place it a second time upon its axis (§ 454.) — It will be at once seen that its equilibrium is disturbed, and that it takes the slanting position of which we have spoken above.

Fig. 134.



A needle may be fitted up in the same manner as we have already described in the first experiment; but instead of suspending it by a wire fork, it will be better to lay the ends of its axis on the edges of the uprights *b*.

When a magnet has been mounted so as to have perfect freedom of motion about its centre of gravity, the angle it makes at any point on the earth's surface with the horizon is called the *angle of the needle's dip* at that place. As has been already said, at all places in the northern hemisphere the north pole is depressed, and in the southern hemisphere the south pole. Instruments intended accurately to measure the magnitude of this angle are termed *dipping needles*, and are very expensive, on account of the difficulty found in practically constructing them. To estimate the magnitude of the angle made by the needle, the apparatus has a vertical circle of brass graduated into 360°.

§ 445.

The dip of the needle, as well as its variation, differs at different places. There is an irregular curve in the neighbourhood of the terrestial equator, where a needle balances itself perfectly horizontally. This curve, to which Professor August has given the name of the *aclinic line* (it is also sometimes called the *magnetic equator*), does not coincide with the equator, but cuts the latter line in two nearly opposite points in such a manner, that the portion of it situated in the western hemisphere runs south below the equator of the earth, and the portion contained in the eastern hemisphere runs northward of tho same line. From this line northwards, the dip of the north pole of the needle increases nearly in the same proportion as the latitude of the place; a similar increase in the dip of the south pole obtains in the southern hemisphere. If we connect those places in the two hemispheres where the dip is equal, we obtain *lines of equal dip*, or *isoclinic lines*, which surround the globe, running nearly parallel with the magnetic equator. It is worthy of remark, that a striking coincidence is found to subsist in the position of these curves, and that of the isothermal lines. (§ 428.) This seems to indicate that the earth's magnetic condition is in some way connected with terrestrial heat.

The magnetic equator is not a circle, but rather a curve of double curvature with many deflections, especially in the neighbourhood of the nodal points, or points of intersection. The position of these last named points, and indeed that of the equator itself, is extremely variable; and as far as observation has yet shown, it appears to move progressively from east to west. One of these nodal points is at present near the Isle of St. Thomas, in 3° E. lon.; and the other in the Pacific Ocean, about 142° E. lon. The greatest declination of the magnetic equator from the equinoctial line amounts to about 20° in the northern hemisphere, and is attained in 53° E. lon., or thereabouts; and its greatest southern declination of 12° in the western hemisphere, is near the Bay of Bahia, about 35° W. lon. — The dip in Europe ranges from 60° to 70°; over the magnetic pole of the earth it must amount to 90°. — In the year 1836, in the northern hemisphere, proceeding from the magnetic equator northwards, the dip was 54° 49′ at Pekin, 61° 42′ at Rome, 68° 32′ at Brussels, and 71° at Petersburg; in the southern hemisphere it was 14° 50′ at St. Helena, and 13° 30′ at Rio Janeiro.

A. von Humboldt gave the first impulse to the construction of charts, which might show the dip of the needle in much the same manner as the magnetic maps we have just described exhibited its declination: in the execution of his plan he received important assistance from Hansteen, Ermann, and Duperrey.

§ 446.

The phenomena of the declination and dip of magnetic needles at the earth's surface are seen to coincide exactly with the effects produced by a bar-magnet on such needles; hence we are compelled to infer, that our planet is itself a bipolar magnet, whose poles do not exactly coincide with the poles of the earth's axis, but which lie somewhere near the latter points; that, agreeably to the fundamental law of magnetic influence, they attract only unlike poles; but as the north pole of a magnet dips in the northern hemisphere, and the south pole in the southern hemisphere, it follows, that the northern hemisphere has a south polar magnetism, and the southern hemisphere a north polar magnetism.

For this reason some philosophers, the French especially, have called that pole of the needle which points to the north, the south pole, and the end which points to the south, the north pole.

By the magnetic poles of the earth, of which we have spoken in this and the preceding paragraphs, the reader is not to understand fixed points, but regions, in one of which the south polar magnetism is concentrated, and in the other the north polar magnetism, the fluid itself being supposed to be distributed over the whole of the earth. Hansteen was of opinion that there were two of these points in the northern hemisphere, and, reasoning from analogy, that there were two also in the southern hemisphere, these magnetic poles being near to the poles of the earth's axis. One of these he believed to be situated in North America, a little west of Hudson's Bay, in 80° N. lat. and 96° W. lon.; the other in North Asia, in 81° N. lat. and 116° E. lon.; the southern magnetic poles he placed a few degrees farther from the south pole. Gauss's more recent observations have, however, led to the belief, that there exists but *one* such pole in each hemisphere. Sir James (then commander) Ross found one of these during his arctic expedition of 1829—

1833, in the year 1831, to be in the vicinity of Hudson's Bay, in 70° 5′ 17″ N. lat., and 114° 55′ 18″ W. lon., where the dipping needle was within 1 minute of being vertical; a difference which may fairly be attributed to an error in the observation. The actual existence of the magnetic pole in that spot was further proved by noticing that the variation needle, when carried round, always pointed to that spot, and when in that station followed the course of the sun in his circuit, around the horizon. Gauss theoretically fixes the position of the magnetic pole in the southern hemisphere in 72° 35′ S. lat., and 152° 30′ E. lon.

The inductive effects of the earth also prove its magnetic state, inasmuch as they bear a striking analogy to the induction of magnetism by ordinary magnets in bodies susceptible of this influence. (§ 439.) These magnetic effects of the earth are attributed to the operation of *terrestrial magnetism.*

Expt. To verify the inductive power of terrestrial magnetism, procure a bar of soft iron from 2 to 3 feet long; a bundle of iron wire, insulated by a wash of sealing-wax dissolved in naphtha, or spirits of wine, will do still better; a common variation-needle moving freely on a point will then show the various magnetic states of the iron bar caused by shifting its position with regard to the earth.

Hold the bar in a horizontal position, and at right angles to the direction of the needle, so that one of its ends shall be over the middle of the latter; the needle will be unaffected, for the bar will be in a state of magnetic indifference. Now shift the position of the bar, inclining it gradually in the direction of the magnetic meridian, and it becomes magnetized, and acquires two distinct poles, its maximum intensity being attained when held parallel to the dipping needle at the place of observation. Bring the lower end near to the north pole of a variation needle, and its north polarity will be shown by its repelling the needle; bring the upper end to the south pole of the needle, and by repelling it, it will become evident that this end of the bar is a south pole. Reverse the position of the bar, and you at the same time reverse its poles.

These phenomena are generally spoken of as the results of *magnetism by position.*

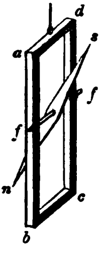
The experiments performed by Barlow with large iron balls, called *terrellas*, are extremely instructive. These balls, by the inductive influence of the terrestial magnetism, acquired a magnetic condition answering to that of the earth itself. On one of these globes, 13 inches in diameter, he traced the existence of a magnetic axis and a magnetic equator. The former had the same position as a dipping needle, and when small and delicate magnetized needles were placed on the latter in their normal position, they suffered no disturbance; whereas, in any other part of the sphere they exhibited both a declination and a dip.

§ 447.

The position of the poles of a needle and its dip, varied as we find them both to be in different parts of the world, must be regarded as the result of the attraction exerted by the north and south magnetism of the earth. This force is put forth in two directions upon magnets, viz. horizontally, by which the position of a needle is determined, and vertically, by which its dip is regulated. If a magnet be perfectly mobile, both horizontally and vertically, it will obey both these forces and take up a position which expresses the *mean force of terrestrial magnetism.* Every dipping needle that has motion in the magnetic meridian gives this line; and if we conceive a plane to intersect the axis of such a needle at right angles, we shall have its magnetic equator. If a dipping needle be so placed, that its plane of motion stands at right angles to the magnetic meridian, or if its axis lie in the latter, then the needle will not be acted on by that part of the terrestrial magnetism which is exerted in the plane of the horizon, but only by that which acts in the vertical plane; it will consequently assume an upright position.

The most simple form of magnetic apparatus in which a needle can have this two-fold free motion, is that represented in *fig.* 133., and described already in the *first experiment*, § 344. This construction will not, however, give a very accurate instrument. Care must be taken to fix the needle *n s* in the cork, and to balance it as exactly as possible before it is magnetized; and in magnetizing it, its position must not be disturbed. *Fig.* 135. represents a more accurate kind of instrument. *n s* is a magnetized needle; in the centre of gravity it has an axis placed at right angles to itself, and about which the needle turns with extreme facility on the ends of two screws *f f*. These screws go through the parallel uprights of a light brass frame *a b c d*, that has a small hook at top, in which an untwisted silk thread may be fastened, and the whole apparatus can be hung up under a bell-glass.

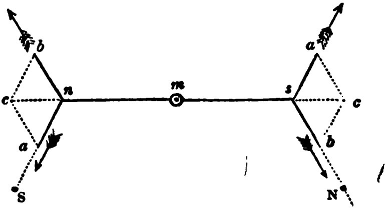
Fig. 135.



The following observations will prove that the inclination of such a needle gives the direction in which it is acted upon by the resultant of the terrestrial magnetic forces.

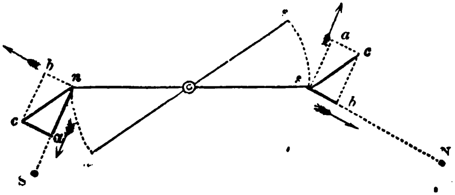
Let S and N be the two magnetic poles of the earth, and let *n s* be a magnet moving freely, both horizontally and vertically, about its centre of gravity *m*. The

Fig. 136.



attractive and repulsive influence of the poles N and S, in the horizontal direction, impart to the needle its position *n s*, with regard to the poles, such that its axis lies in a line joining N and S: any further approach towards the more powerful pole will be prevented by the suspension of the needle on the fixed point *m*. The needle's dip will be regulated by that portion of the magnetic influence which is exerted in the vertical plane. We will assume first, that the needle is situated just midway between the two poles N and S, and, consequently, every part of it will be equally solicited; and the point *n*, for instance, will be drawn in the direction *n* S, by the pole S, just as strongly as the point *s* is repelled in the direction *s a*. The line *n a*, which expresses the magnitude of this attraction, must therefore be equal to *s a*; and as the distance of the earth's poles from these points is so great the two lines *n a* and *s a* may be regarded as parallel. The other magnetic pole N acts in like manner, attracting *s* as powerfully in the direction *s* N, as it repels *n* in the direction *n b*; whence also *s b* is equal to *n b*, and these two lines are likewise parallel. Now, by the parallelogram of forces (§ 23.), *n c* is the resultant for the point *n*, and *s c* for the point *s*; but they are both equal, and in exactly opposite directions, whence the needle will be held in a horizontal position. Next, let us take the case when the needle *n s* is nearer one of the earth's magnetic poles than it is to the other, and let us suppose it to be nearer to S; then the point *n* will be as strongly solicited by the pole S, as *s* is repelled by it, so *n a* will be equal to *s a*; the pole N will attract *s* as powerfully as it repels *n*, whence $sb = nb$. But the attractive force of N is less than that of S; for N is more remote than S, *n b* and *s b* will therefore be less than *n a* and *s a*. The resultants *n c*

Fig. 137.

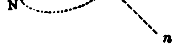


and *s c* will in this case be equal and parallel, but not exactly opposite to each other: they will therefore cause the needle to turn about its fixed point, and it will only come to rest in the direction *n′ s′*, parallel to the resultants *c n* and *c s*; this therefore, will be the dip of the needle.

§ 448.

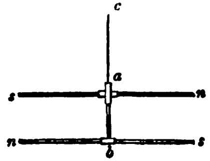
It is important for many purposes to have magnetic needles on which the earth cannot exert any directing influence: needles of this kind are called *astatic needles.* A magnet moving freely can be rendered independent of terrestrial magnetism, by giving its axis of rotation precisely the inclination which a dipping needle placed in the magnetic meridian would have taken. Thus, if *n s*, (*fig.* 138.) were the dip of such a needle, all that would be required would be to place the axis *a b* of the needle N S in the direction *n s*, and it will be immediately converted into an astatic needle. The earth acts in the direction of this fixed axis upon the needle, whose movements are performed in the plane of the magnetic equator; it will, therefore, rest in any position whatever in this plane.

Fig. 138.



Another, and for many purposes a more useful, sort of astatic needle may be thus constructed. Two needles (*fig.* 139.) whose magnetic powers are as nearly equal as possible, are fastened on a common axis *a b*, which is suspended by an untwisted silk thread *a c*; the needles are parallel to one another, and the north and south poles of the upper needle are over the south and north poles of the lower one. By means of this arrangement, neither of them can assume any particular position with respect to the

Fig. 139.



poles of the earth, and when once brought to a state of rest, their direction is affected by the exertion of the slightest attractive force.

A still more simple, and at the same time very serviceable, astatic needle is obtained by magnetizing both ends of a common variation needle with the same kind of magnetism and of equal intensity, *i. e.* by making both ends equally powerful north or south poles. It will soon be explained (§ 454. *second expt.*), how these needles may be prepared with but little trouble.

The last-named variety of astatic needles is principally used for detecting very feeble magnetic influences. The application of this instrument will be noticed in the sections on Electricity and Electro-magnetism.

§ 449.

The *intensity* of the terrestrial magnetism is found to vary as much as the declination and dip of the needle at different points on the earth's surface. Near to the magnetic equator it is most feeble, and increases gradually as we approach the poles; it increases, therefore, as we travel from the warmer to the colder regions of our planet. Those places where the intensity has been found to be equal have been connected by lines, first called by Hansteen *isodynamic lines*, which in both their form and position resemble the isoclinic curves. With these, however, they do not exactly coincide, but approach still more nearly to the isothermal lines. On the western continent they extend much farther south than on the eastern, so that in equal latitudes the magnetic intensity is greater in America than in Europe, and greater in Europe than in Asia. The stations of minimum intensity, however, are not ranged in a continuous line about our earth, but seem rather isolated, lying near S. Africa, under the line of greatest terrestrial heat.

Hansteen constructed a chart on which he laid down the isodynamic curves: this map has been since copied more than once. The magnetic intensity observed by A. von Humboldt in 7° S. lat. and 15° W. lon. from London, is assumed as the unit. A glance at one of these maps will show that, in the western hemisphere, the terrestrial magnetism is of greater intensity than in the eastern, and that, on the whole, it is greater in the northern than in the southern hemisphere. The absolute minimum which is found in Southern Africa in 20° S. lat. barely exceeds 0·8, and the maximum near Hudson's Bay in 41° N. lat. is only 1·8; whereas, in the same latitude in Western Europe and in Eastern and Western Asia, it is no more than 1·3, and in the most northern parts of Siberia, in lat. 70°, the intensity is not more than 1·7. The mean intensity for Europe may be reckoned at about 1·35. Thus, the intensity at Madrid is 1·294; at Rome, 1·264; at Florence, 1·278; at Vienna, 1·325; at Paris, 1·348; at Berlin, 1·364; at London, 1·33; at Stockholm, 1·342; at Petersburg, 1·403:

Gauss, on the other hand, has more recently endeavoured to express the total effect of terrestrial magnetism by assuming a certain value as the unit. To obtain this, he selected three stations on the earth where the intensity of the terrestrial magnetism was believed to have a maximum value, and two where it had a minimum. Of the former, he found one in N. America near the north magnetic pole; the second, in that part of Siberia where Hansteen thought the second magnetic pole was to be found; and the third, south of Van Dieman's Land, near the south magnetic pole. The intensities of the magnetism at the first three points he estimated at 6·1614, 5·9113, and 7·8982, respectively. The two points of minimum terrestrial magnetism lie near the equinoctial; the one, north-east of New Holland; the other, near St. Helena; their intensities are valued at 3·2481, and 2·8281.

The intensity of the terrestrial magnetism has been estimated by its influence on a magnet's oscillations. These oscillations are precisely similar to the vibrations of a pendulum, the motive power in the latter case being terrestrial gravitation, while in the former it is magnetism. Now, by the laws of a pendulum's motion (§ 101.), we know that the time of an oscillation may be represented by the expression

$t = \pi\sqrt{\frac{l}{2g}}$, t being the time of the oscillation, l the length of the pendulum, and g the intensity of the force of gravity: the times in which the same pendulum will perform an oscillation at stations where the forces of gravity g and g' are unequal, will themselves be unequal: in fact, they will be

$$t : \mathrm{T} = \pi\sqrt{\frac{l}{2g}} : \pi\sqrt{\frac{l}{2g'}},$$

or

$$t^2 : \mathrm{T} = \frac{1}{g} : \frac{1}{g'};$$

whence

$$g : g' = \frac{1}{t^2} : \frac{1}{\mathrm{T}^2};$$

i. e. the intensity of the force of gravity is indirectly as the squares of the times of the pendulum's oscillations.

Again; as the number n and N of oscillations performed in equal times is inversely as the length of an oscillation, it follows that

$$g : g' = n^2 : N^2;$$

i. e. the squares of the number of vibrations performed in a given time by the same pendulum are as the intensity of the force of gravity.

Now let this be applied to magnetized needles, and for the force of gravity substitute the magnetic intensities m and M, then

$$m : M = \frac{1}{t^2} : \frac{1}{T^2},$$

or $$m : M = n^2 : N^2;$$

i. e. the intensity of terrestrial magnetism at different places on the earth's surface, when applied to magnetic needles, is indirectly as the squares of the times of their oscillations, and directly as the number of oscillations when the times are equal.

Suppose, that at the station A the needle makes a certain number of oscillations in 100 seconds, while at B, it would perform the same number in 71 seconds; or, expressing it in other words, the needle makes 71 oscillations at A in the same time as it performs 100 in at B; then the intensities of the magnetic influence m and M at the two places will be

$$m : M = \frac{1}{100^2} : \frac{1}{71^2},$$

or $$= 71^2 : 100^2,$$

$$= 5041 : 10000,$$

$$= 0{\cdot}5041 : 1;$$

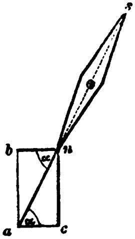
whence the intensity M, at station B, is nearly double that of m at station A.

This mode of experimenting is applicable to both the variation and the dipping-needle. It can be employed with greater advantage to the former, both because it is more easy to hang accurately, and because the duration of its oscillations is greater, as fewer obstacles impede its motion.

By means of a variation-needle we can measure only that portion of the terrestrial magnetism which acts horizontally, and by a dipping needle only that which is exerted vertically. (§ 447.) By means of the parallelogram of forces

(§ 23.), however, we can readily prove, that the intensity found by either of these modes is proportional to the total effect of the terrestrial magnetism.

Fig. 140.



Let *n s*, *fig.* 140., be the directing force of the earth's magnetism, as shown by a dipping needle in the magnetic meridian of a place (§ 447.), and let $n\,a = P$ represent this force, which may be resolved into $n\,b = H$, in the direction of the horizon, and $n\,c = V$ acting in the vertical plane. Now if $\alpha =$ the angle of the dip (§ 444.), it is evident that $P = \frac{H}{\cos.\,\alpha} = \frac{V}{\sin.\alpha}$; *i e.* the total effect of the magnetic influence exerted by the earth at any particular place is found by dividing the horizontal intensity by the cosine, or the vertical intensity by the sine of the angle of the needle's dip.

By observing the oscillations made by a dipping-needle, we may measure the dip or inclination of the needle at any particular place. First, place the needle in the plane of the magnetic meridian, then in a plane vertical to the former; cause it to vibrate in both these positions, and count the number of oscillations made in equal times in each position, and it will be found that the number N performed in the first exceeds that made in the second *n*. In the plane of the magnetic meridian they obey the entire magnetic influence P, but in the vertical plane the needle is acted on only by that portion V of the force which is exerted vertically. We have already found $P = \frac{V}{\sin\,\alpha}$; whence $\sin.\,\alpha = \frac{V}{P} = \frac{n^2}{N^2}$.

But the results found by observing the oscillations which the same needle makes at different places, will give us accurate values for the intensity of the earth's magnetism, if the needle's innate free magnetism undergo no change, but not otherwise. In the small needles which were formerly employed, this rarely happened to be the case, as they are affected by variations in the heat, and still more sensibly by the presence of masses of iron and other similar bodies. To guard against these sources of error, Gauss made use of bars of iron from 1 to 4 feet in length, and weighing from 1lb. to 25lbs., to which he gave the name of *magnetometers*. The weight of these masses, in addition to the other precautions he took, secured these bars from the operation of external influences. This simple but ingenious apparatus surpasses all the instruments previously contrived; for it is capable of indicating the minutest changes that transpire in the intensity of the earth's magnetism, by proportional variations of the magnetometer from its normal position, which changes can be measured to an angle of one second; hence all the magnitudes which it is desired to investigate with regard to the intensity of the terrestrial magnetism, may be found with the most rigid precision.

The oscillation-experiments with common variation needles can be advantageously applied only when we are warranted in assuming that the intensities of the needles themselves undergo no change; with this proviso they may be used for comparing the different powers of magnets, or for estimating the minute magnetic influence of other bodies, as will be shown presently.

§ 450.

Observations made during many years, and the accumulated experience of philosophers have shown, that there subsist both *regular* and *irregular* variations at the same place in the earth's magnetic powers, as indicated by changes in the declination and dip of the needle, and in the magnetic intensity.

The regular variations are such as follow a certain law, and which, as far as we are acquainted with that law, can be calculated beforehand. Professor Baumgartner distinguishes them into *secular*, or such as become evident only after the lapse of lengthened periods, and *periodic* which oscillate in a manner within narrow limits in certain short periods of time.

Of the secular variations, the declination is that which has been longest observed, and is most accurately known: our information as to the dip and intensity rests on fewer data, and is of more recent origin.

Variations were first observed to take place in the declination of the needle in the 16th century, but it was not till the 17th that anything was accurately known as to the rate of these changes. About the year 1600, the needle in Europe pointed to the east of the north; in 1663 it pointed due north; from which time its deviation westwards gradually increased till the close of the preceding century. For a short period after the commencement of the present century the needle was stationary, but for the last 20 years its declination has certainly decreased, and, in all probability, it will continue to do so till it again becomes due north, then the declination will increase towards the east, and when the needle has attained a maximum it will again return. The needle began to retrograde at London in 1819; at Paris, and throughout the greater part of Germany, in 1814. At Berlin, the declination in 1840 was 16° 42′, and the annual decrease is about 3° 8′.

The only observations made on the variations in the dip of the needle, are both few and unsatisfactory; all that is known with certainty is, that at present the dip in Europe is decreasing. In the year 1780, the annual decrease in Europe was from 5′ to 6′; in 1830 it was but 3′; whence it appears that the dip has nearly attained its maximum. According to the observations made in 1840, the dip at Berlin was 67° 53′, with an annual decrease of 3·5′.

Our knowledge of the variations in the magnetic intensity is still more defective, for it is but recently that this subject has been investigated. Hansteen believes, on theoretical grounds, that we may assume the intensity also to be decreasing, and that this decrement in Europe is annually 0·003695.

The diurnal and annual variations of the declination-needle consist in an oscillation eastward and westward of its mean position. The magnitude of the diurnal variation differs according to the situation of the place, and the time of day and year. It appears to be very intimately connected with the generation of heat by the sun. In the middle of Germany, in winter, it is about 8′, and in summer about 16′. In the more southern regions, which lie nearer to the magnetic equator, the daily oscillations become less, and at the equator itself they vanish entirely. Recent observations have placed it beyond all doubt, that storms materially affect these periodic changes in the variation needle. With a clear sky and an easterly or north wind, the fluctuations have been found to be greater than when the weather is cloudy, and a south or west wind prevails. In this case, also, the results seem to be affected by solar influence.

From a comparison of the observations made on the declination of the needle at different places, the following results have been arrived at:—

1.) The time of the greatest declination ranges between 6 and 9 A.M., happening earlier in summer than in winter.

2.) The time of the greatest declination westward is about 15′ past 1 P.M.; but this depends on the season of the year.

3.) The oscillations in summer are greater than in winter. According to Kreil's observations made at Prague, 1839-40, in summer the arcs moved through are three times as great as in winter. The greatest oscillation noticed in any one day, by Gauss, was 20·1′.

4.) The oscillation during the night is inconsiderable.

5.) The mean declination is attained between 10 and 11 A.M., and again between 6 and 7 P.M.

The observations made at Göttingen, in 1834-37, which are extremely accurate, give the following results for each month in the year: the mean values are given:—December, 5·0′, January, 6·7′, February, 7·4′, March, 11·9′, April, 13·9′, May, 13·5′, June, 12·5′, July, 12·1′, August, 13·0′, September, 11·8′, October, 10·3′, November, 6·9′.

Hence the mean for the year is 10·42′, for the winter months, 8·01′, and for the summer months, 12·81′ the greatest declinations occurring in the warmest, and the least in the cold months. The mean declination at Göttingen, of 18° 41′ 10·4″, was, by these observations, ascertained to fall in the months of April or May and September; that is, when, generally speaking, we have the mean temperature of the year.

The fluctuations caused by the weather, as observed at Tübingen, in 1831, amounted on an average to 11·9′ on fine days, and to 10·6′ on cloudy days, the mean annual variation from this cause being 12·6′. Dove's observations at Berlin, in 1830, gave a daily variation of 9′ 45″ on fine days, and 8′ 11″ on cloudy.

Recent observations have further shown, that the dip of the needle is also subject to certain daily variations, which, however, do not accord exactly with the changes in its declination; they appear to depend on the action of the sun upon the earth's surface.

According to Kupffer's observations at Petersburg, in 1831, the maximum dip was attained at about 10 A.M., and the minimum at 10 P.M. It is greater in summer than in winter, when the oscillation becomes exceedingly small, not amounting to more than 4′. The following are the results obtained by Kreil, who, in 1839, made observations for each hour of the day. The dip reached its maximum and minimum thrice in the course of the day. In summer, the first maximum was attained between 8 and 9 A.M.; in winter, between 10 and 11 A.M. The third maximum is reached at noon, which, during many months, exceeds the other two maxima; the third minimum is also attained in the course of the morning.

Recent experiments have established beyond all doubt the fact, that the intensity of terrestrial magnetism is in like manner subject to periodical variations. The result arrived at is, that an alternation of a minimum and maximum obtains at certain periods of the day and year, and that, in strict analogy with the other magnetic influences, the intensity is greater in summer than in winter.

The observations made by Kupffer at Petersburg, in 1831–2, with a very delicate dipping needle, show that the total power of the magnetic intensity is greater in the evening than in the morning; that it decreases from April to September, from which month till April again it probably increases. Kupffer is of opinion that the moon exerts an enfeebling influence on the magnetic intensity. Moser and Riess, at Konigsberg, found the maximum intensity was reached at 8 P.M., and the minimum at 9 A.M. The results of Kreil's more recent experiments, as conducted by Professor Baumgartner, are the following: — The horizontal intensity of the earth's magnetism shows a daily variation with one minimum and one maximum; the former happening in summer at 10 A.M., and the latter at 8 P.M. In winter the two extremes are reached rather later than in summer. The intensity of its total influence attains one maximum early in the morning and a minimum in the afternoon, so that a second maximum seems to be attained at 8 P.M. This last point, however, needs to be further investigated. The influence of the moon on the horizontal intensity was clearly ascertained. These laws have been deduced from a series of observations made on the horizontal intensity at Milan during a period of three years compared with those made at Prague in 1839–40.

The irregular magnetic variations are accidental *disturbances* in the earth's magnetic power, generally of but short duration: they are indicated both by the variation and the dipping needle. These disturbances are caused by the aurora borealis, by earthquakes, by volcanic eruptions, by sudden changes in the temperature, by storms and alterations in the quarter from which the wind blows.

During the appearance of the northern lights the variation needle is sometimes deflected from 5° to 6°, and the phenomenon exerts an influence even where it is not visible. Kämtz has discovered that the winds perceptibly affect the needle, and that in the north and north-east they cause it to point more towards the east than in the west and south-west. The other causes of irregular fluctuations in magnetic needles exert a far less powerful influence than that exerted by the aurora borealis

Kupffer is of opinion that these extensive disturbances of the needle are owing to a sudden displacement in the magnetic lines on the earth's surface. He considers that this hypothesis furnishes the most natural explanation of the simultaneous occurrence of these phenomena at points on the earth's surface very remote from each other, and that it also accounts for the needle's moving during these irregular disturbances in a direction opposite to that in which the magnetic lines run.

It has been observed already (§ 432.) that rather more than ten years ago the indefatigable A. v. Humboldt was the founder of the Magnetic Association, which has since extended itself throughout the greater part of the world. The object of this association is to investigate the causes of the various magnetic changes in the earth's magnetism, and, if possible, to ascertain precisely the influence it exerts. For this purpose simultaneous observations are made with Gauss's magnetometers at various stations at and beneath the earth's surface. The communications addressed to this society have shown, that not only the greater variations in the earth's magnetic, influence, but also the most minute, nay, even the irregular, disturbances have been perceived simultaneously at points far asunder. Although the changes observed did not universally coincide in degree, yet their occurrence at the same time proves beyond question that they are connected, and establishes the fact of a remarkable coincidence in these phenomena throughout the world.

§ 451.

One question remains to be answered, — What notion shall we form of the earth's magnetism, which shall enable us to explain satisfactorily both the constant and varying magnetic phenomena that present themselves to our notice? Until lately philosophers have agreed in ascribing to the earth a sort of independent magnetism, and they have further assumed that this force had its seat in the interior of our planet. Of these theories Hansteen's is both the most complete and the best supported. He conceived that all magnetic phenomena were owing to a magnetic power resident in the interior of the earth, and that its influence was especially displayed externally at four points. He further supposed that this influence was put forth with equal intensity in two opposite directions or axes, the poles of these axes being at a considerable distance below the earth's surface. To account for the variations which occur in the needle's declination and dip and in the magnetic intensity, he attributed to these axes, and so, of course, to their poles, a progressive motion, in consequence of which the two magnetic poles of the northern hemisphere point more and more towards the east, and those in the southern hemisphere more towards the west. If these assumptions are admitted, this theory will adequately explain all that was formerly known with regard to the various phenomena of terrestrial magnetism as well as the principal regular variations to which it is subject; yet, on the other hand, it must be confessed that the researches of modern science have shown many bodies to possess magnetic properties which were not formerly believed to have any; that for many important reasons, some of which will be adduced presently, it appears to be very doubtful whether the earth has any magnetic axes; and whether the interior of the earth is the seat of magnetic influence at all is still more so. One of the most weighty objections to this theory is to be found in the now well ascertained diurnal and annual variations in the magnetic declination and dip, which the observations of the Magnetic Association have proved to coincide with one another remarkably in different parts of the world. This discovery, added to the fact that the northern point of magnetic convergence very nearly agrees with the point of the earth's minimum superficial heat, and the evident influence of that agent on the phenomena of the earth's magnetism and on magnets in general (see § 452. and 462.), have led to the construction of another theory, which seems to afford a more natural explanation than is furnished by Hansteen's hypothesis. The main features of this theory are, that the earth's crust, and not its interior, is the seat of magnetism; that in the northern hemisphere a north, and in the southern a south magnetism predominates — the intensity in each case increasing from the equator towards the pole, but not uniformly in the two hemispheres. The resultant of this influence at any point on the earth's surface is caused by the separation of the two magnetic fluids in the component particles of the earth. The depth to which this supposed separation extends is intimately connected with the mean heat of the earth's crust, if it is not actually consequent upon it. According to this theory, axes and poles have no actual existence; but are merely mathematical ideas, which represent to our minds the places where the influence of the single forces is combined. The impartation of this force will naturally be subject, through the excitation of heat by the sun, to constant variations, which will return as periodically as the action of the sun itself. The changes in the earth's magnetic powers are accordingly held to be dependent on the temperature of its surface; the diurnal variations being caused by the daily increase and decrease in the temperature, and the annual variations by the periodical fluctuations above and below the mean annual temperature. The position and form of the magnetic equator, and especially the whole system of the isoclinic curves, is regulated by the distribution of heat in the two hemispheres. Lastly; the nature and degree of the needle's declination and the position of the isogonic lines are explicable if attributed to the local temperature.

No direct evidence has yet been obtained to show whether magnetism is confined to our earth and the substances it contains, or whether this agent is common to it with the other heavenly bodies. Some philosophers are of opinion that they have detected traces of its operations in them; and certainly the points of resemblance, as to form, motion, the position of their axes, &c. among the planets are so numerous, that we are disposed to think that magnetic influence extends even far beyond the limits of our solar system.

IV. THE ARTIFICIAL PRODUCTION OF MAGNETISM, THE MEANS OF EXCITING AND INCREASING IT, AND THE DIFFERENT METHODS BY WHICH TO ENFEEBLE OR DESTROY IT.

§ 452.

The *intensity of the magnetism* of which any magnetizable body is susceptible, depends on the coercive power (§ 441.) of the substance composing it. The less this force or the resistance which a body is able to offer to the separation of the magnetic fluids, the more easily is it magnetized — the more readily too does it lose the whole or a part of the magnetism it had acquired. The greater the coercive power, or the more powerful the resistance offered, the more difficult is it to magnetize the body, and the longer does it retain the magnetism imparted to it, *i. e.* the longer does it hold the two fluids asunder. In non-magnetizable bodies, this resistance altogether prevents their receiving magnetism; in such as are magnetizable, on the contrary, it is the cause which to a certain degree maintains the separate condition of the two polar forces. According to Barlow's experiments, pure soft iron offers the least resistance to magnetization, next soft steel, then hardened steel, and lastly cast iron.

Repeated observations have shown, that the resistance of magnetizable bodies is greatly modified by heat; that by raising their temperature this resistance is lessened; so that, for every body of this class, there exists some particular temperature, at which it is entirely destroyed. On being heated to this point the body becomes insensible to the most powerful magnetic influence, and is consequently incapable of being magnetized. The limit at which iron and steel continue susceptible of magnetic influence, is a deep red heat of about 1400° Fahr. When very near this temperature, they still retain a coercive force, which enables them to acquire the most powerful magnetism; but if heated beyond this point till they become white, they both lose all sensibility to magnetic influence. Thus heat seems to exert a controlling power over a body's capability for yielding to magnetic influence; it does not appear that heat ever induces magnetism; it is merely a modifying cause, and the different degrees of magnetic susceptibility depend on the cohesive force of the substance as affected by heat.

There is also a limit to the quantity of magnetism, that a body can receive and retain. This limit is called the *point of magnetic saturation*, and from what has been just advanced, it is evidently dependent on the coercive power of the substance. Whether any particular body has or has not attained this point, depends on the intensity of the magnetic influence to which it is subjected, and also on the length of time it has been in operation, for if the force be too feeble, and the time too short, the point of saturation will not be reached. A body may even be *overcharged*, *i. e.* so extreme a tension of its magnetic forces may be induced, as can be maintained only whilst the body is acted upon by the magnetising body; and on the removal of the latter, the coercive force more or less slowly regains a portion of its power. The polar forces are maintained in an effective state by connecting the poles of the magnet with some other body, such as soft iron, of lower coercive power than itself.

Hence, whenever we wish to excite a mere temporary magnetism, we employ pure soft iron; but when we desire the magnetism to be permanent, we use hardened steel. All artificial magnets are made of hardened steel, though nickel and cobalt may also be rendered permanently magnetic.

The steel best suited for artificial magnets is of a fine grain, of uniform structure throughout, and free from flaws. A principal requisite is, that it should possess a proper degree of hardness, and that it should be equally hardened throughout the entire mass; for, if too hard, it is extremely difficult to impart to it any magnetic virtue; and if too soft, it readily loses it when given. It has been found most advantageous to make the steel in the first instance brittle, like glass, and then to heat it a second time, till it becomes of a straw, or violet colour.

The capacity and tenacity of artificial magnets are also affected by their form and dimensions. It has been ascertained that the breadth of a bar magnet should be about one-twentieth of its length, and its thickness from one-fourth to one-third of its breadth. In a horse-shoe magnet, the space between the two poles ought not to be greater than the thickness of the bar of which the magnet consists. Lastly; it is necessary that both bar and horse-shoe magnets be well polished, and that their faces be as level as possible.

The poles of a magnet, when not in use, should be in contact with a *keeper*, especially the poles of a horse-shoe magnet. The keeper tends to maintain, and even exalt, the power of the magnet, whose poles are thus employed in producing the opposite magnetism in the respective ends of the keeper, which should be made of the purest and softest iron. The keeper should be in absolute contact with the two poles of the horse-shoe magnet, or with the opposite poles of two bar magnets, which should be placed in a line.

§ 453.

There are various methods of magnetization, but the most effectual are, of course, such as most quickly and completely overcome the resistance. Those known as yet are — 1.) By immediate contact with magnets, either natural or artificial; 2.) by induction, *i. e.* by being brought into the vicinity of such magnets; 3.) by various mechanical manipulations; 4.) by the solar rays; 5.) by electricity.

§ 454.

The most common and the readiest method of magnetization is that first named. It admits of three modifications; that is to say, the bar to be magnetized may have the magnetic virtue imparted to it by mere *contact* with another magnet, or by *drawing the pole* of the latter along its surface, or by being held in contact with the pole of a magnet, and then being struck with a piece of soft iron.

By mere contact the end of the steel which touches the pole of the magnet acquires a dissimilar magnetism to that of the pole with which it is in contact, and its other end acquires a magnetism similar to that of the pole. The magnetic equilibrium of the body is disturbed by the pole at the point of contact, the dissimilar magnetism is attracted, and the similar repelled; and if the body's mass is not too large, this effect is propagated throughout the whole of the body.

First Expt. Touch one end of a sewing needle with the north pole of a magnet; on separating them you will find that the end which was in contact has become a south pole, and the other a north pole.

Second Expt. Touch a needle in the middle with the north pole of a magnet, its middle will be a south pole, and its extremities will be north poles We have thus obtained a magnet with three poles, and in a very simple manner an astatic needle of more or less accuracy. (§ 448.)

Third Expt. On a clear polished steel surface draw any figure whatever with the pole of a powerful magnet, then sprinkle iron filings upon the plate, and they will remain suspended wherever the magnet has passed.

The magnetism thus imparted is, however, less powerful than that communicated by drawing the pole of a magnet several times along the bar which is to be magnetized. The touch is said to be *single* or *double*, according as it is effected with one pole, or with the opposite poles of two magnets at once.

The process may be explained in accordance with the theory advanced in § 441., if we suppose the pole of the magnet which is drawn along the bar of steel to separate the polar forces in every particle of the steel in such a manner, that the opposite magnetism to its own is excited in the direction in which it is moved. This motion will correspond exactly to that which may be observed in iron filings, strewed on a smooth plate of glass, when a magnet is passed along the under-surface of the glass. At the points above the poles, the particles of iron are seen to stand upright, the ends next the pole have an opposite magnetism to it, the ends more remote a similar magnetism. As the pole of the magnet is moved forward, the particles of iron fall down so as to turn their dissimilar poles to the pole of the receding magnet.

The *single touch* is performed by placing one pole of a magnet in the middle of the steel bar, and then drawing it evenly along to the end of the bar; when it has reached the end, the magnet is returned again through the air to the middle of the bar, and the stroke is repeated in the same direction. When this has been done several times, place the other pole in the middle of the bar, and proceed as before. Two magnets may be placed together with their dissimilar poles in the middle of the steel bar, and then be moved in opposite directions towards its two extremities. Each end of the bar which has been thus treated becomes a pole opposite to that with which it has been stroked; *i. e.* the end which has been operated on with the north pole of the magnet becomes a south pole, and *vice versa.* The bar will be impregnated more powerfully if its ends are laid on the poles of two magnets so that contrary poles of the bar and of the magnets may be in contact. This is the mode most generally adopted in forming an artificial magnet to be used as a needle.

To magnetize a bar of steel by means of the *double touch,* two bar or horse-shoe magnets are fastened together, so that their dissimilar poles may be about $\frac{1}{4}$ of an inch asunder. This will be done most conveniently by inserting a small wedge of wood or paper between them, and tying the magnets together. The apparatus thus arranged is placed vertically on the middle of the steel bar, and is then drawn towards the end of it, care being taken that neither of the poles glides over the end of the bar; the magnet is then returned towards the other end, and so on. Instead of thus combining two bar magnets, a horse-shoe magnet may be used if its poles lie pretty near together. In either case, the process is concluded by drawing the magnet only half way along the bar, and then sliding the magnets off sideways. The poles will be dissimilar to those of the magnet. It will be found advantageous to lay the ends of the bar on the poles of two magnets in the same way as when the single touch is used. The *cross touch* is merely a modification of this experiment, by which the operator is enabled to magnetize two bars of steel at once. This can, however, be better performed otherwise, as we shall explain presently.

A bar in the form of a horse-shoe is very readily magnetized, as its two ends are easily connected by means of a keeper, whilst the magnet is being drawn across it, and thus the point of saturation is sooner arrived at. The methods already described can be applied to the magnetizing of bars in the form of a horse-shoe; but the following mode, invented by Hoffer, is superior on account both of its simplicity and effectiveness.

Fig. 141 *a.*

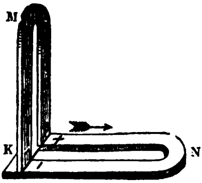
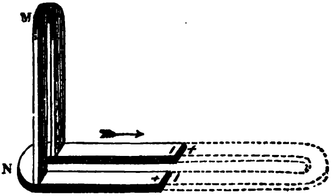


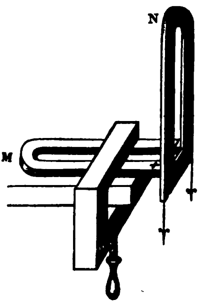
Fig. 141 *b.*



If there be only one horse-shoe N to magnetize (*fig.* 141 *a.*), it will be best to set it flat on a table, and laying against its ends a piece of iron as a keeper K, place a horse-shoe magnet M, whose legs are at exactly the same distance asunder as those of the bar to be magnetized, with its poles perpendicular to the keeper; and holding it still in this position, draw it along towards the bent part of the horse-shoe, on reaching which the magnet is to be brought back to its original place on the keeper without touching the bar as it returns. It is then to be drawn as before along towards the curved part of the bar. After this has been performed from four to six times, the steel will generally be found to have acquired a pretty strong magnetic power; the polarity of each leg will be similar to that of the leg of the magnet which stands on it. The touch may be performed in exactly the opposite direction, the magnet being drawn (M, *fig.* 141 *b.*) from the curved part N of the horse-shoe towards its extremities, and in this case the keeper will not be required.

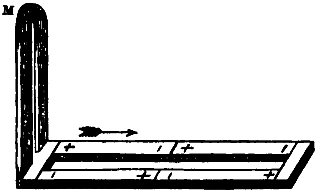
Each leg too will acquire an opposite magnetism to that of the pole which rests on it. If it is wished to magnetize two equal horse-shoes at once, they are placed, as shown in *fig.* 141 *b.*, with their ends close together, so as to form a sort of ellipse, and the magnet M is drawn from end to end. — If the magnet be large and heavy, say 10lbs or more in weight, these manipulations would be difficult, or altogether impracticable. The arrangement made by Von Vest may, therefore, be adopted with convenience. The magnet M (*fig.* 142.) is laid on a table, so that its poles project over the edge; it is secured in its position, either by means of clamps, or by putting a heavy weight on the bent part of it. Then hold the horse-shoe N you desire to magnetize in a vertical position against the magnet, a keeper being previously held to the ends of the horse-shoe. Be careful that the end intended to be made the north pole of the horse-shoe be in contact with the north pole of the fixed magnet. Now press the horse-shoe down in the direction indicated by the arrows in the diagram till the curved part touches the poles of the magnet; then invert the shoe, so that the keeper comes uppermost; place the similar poles together, and move the horse-shoe upwards till the curved part again touches the poles of the magnet. Once more reverse the position of the plate, so as to place it just as when the operation began. The process may be repeated so long as is requisite, care being taken to keep the similar poles together. The touch may in this case be reversed, and the keeper may be dispensed with, only minding to put that leg of the plate which is marked for a north pole against the south pole of the magnet. With regard to the relative efficiency of these different modes of touch, Von Vest's experience goes to prove, that it depends on the individual peculiarity of the steel itself, as he found that some plates were more powerfully magnetized by the first method, and others by the second or third. Von Mohr's method is precisely the same as Hoffer's second, excepting that before the magnet is detached from the horse-shoe it is used to impregnate, a keeper is placed against each of them.

Fig. 142.



This method of touch may also be employed for magnetizing two or more bars at once. For this purpose lay them on a table parallel to one another, and place a horse-shoe magnet with its poles perpendicularly on them, as shown in *fig.* 143., near one of the keepers, by which the ends of the bars are connected. Draw the magnet along the bars to the other end over the keeper, and return it without touching the bars to its original place, and repeat the process a few times. Turn the bars over and treat the other side in like manner, without, however, breaking the connection established by the keepers. Those ends of the bars, first touched by the magnet, will have the same polarity as the poles by which they were respectively touched.

Fig. 143.

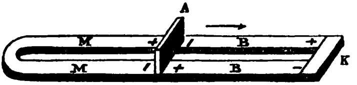


A peculiar variety of bar magnets is that known as the *transverse magnet*, whose poles are not at the ends but at the sides: these magnets have always some even number of *polar lines*. They are made by thrusting 2, 4, 6, &c. bar magnets through a ring in the direction of its diameter, and with their unlike poles opposite each other; a sufficient space is left between these magnets to pass the bar between them which you desire to magnetize, so that it may touch them as it is drawn through.

A third method is to place the bar you wish to magnetize against the pole of a magnet, and then draw a piece of soft iron, such as the keeper of the magnet, from it several times along the bar. By this method a magnetism may be imparted, at least as powerful as by either of the former.

The following will be found the most convenient arrangement: — Lay the magnet, a horse-shoe will be found the

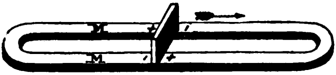
Fig. 144.



best, on a table as shown in *fig.* 144. M M; against its poles lay the two bars B B, the dimensions of whose ends should correspond with those of the magnet: connect the more remote ends by means of a keeper K. Now lay the other keeper A, by means of which the magnetism is to be imparted on the poles of the horse-shoe magnet, across the bars, and draw it evenly along to the other end, as shown by the arrows, until it becomes parallel to the other keeper, when it must be again put in its former position, taking care in replacing it not to touch the bars; and continue this process some five or six times, when the bars must be turned over to be magnetized in like manner, the keeper at their extremities not being disturbed. The operation is now completed: the horse-shoe magnet should now be closed by means of a keeper, and the bars should be disengaged from it by slipping them off sideways. The bar magnets thus formed will be found to have at their points of contact with the horse-shoe magnet an opposite magnetism to it, agreeably to the laws of magnetic induction: this is shown in *fig.* 144., by the symbols + and —

To magnetize a bent piece of steel by this mode, it must be laid as is shown in *fig.* 145., with its two ends in contact with the poles of a powerful horse-shoe magnet, the ends being previously marked; place the dissimilar poles together, and the two horse-shoes will enclose a space. The feeder is now to be drawn along the horse-shoe just as it was drawn along the bars; when it reaches the curve it is to be replaced, and the process repeated: turn the whole over without separating the poles, and treat the other side in the like manner.

Fig. 145.



This mode may be adopted with advantage on account of its simplicity, and the ease of the manipulation, as the keeper can be more readily moved than the magnet, if it be of large size. Experience has further shown it to be very effective. As far as I know, this mode has not yet been generally used. Jacobi, the philosophical instrument maker of Dresden, communicated it to me not long since; he assured me that he had been able, by this manipulation, to impart powerful magnetic properties to steel bars, which he had failed to magnetize to any extent by other modes; that his plan was to present *one* of the poles of the bar he wished to magnetize to one of the poles of the horse-shoe magnet which was to impart the magnetism, taking care that they should always be dissimilar poles, and then to draw the keeper along from the magnet over the bar. Jacobi did not close the poles of the bars which were not in contact with the magnet by means of a keeper; but I have repeatedly performed the experiment, and have always found that by connecting both poles the intensity of the magnetism was considerably increased. The efficiency of this mode of operation will be obvious on considering the following results: — I procured a steel bar weighing 1 lb. I bent it into the form of a horse-shoe, and stroked it 6 times according to Hoffer's method; it was then able to carry 21 lbs. 9 oz., or 21·56 times its own weight: it was then deprived of its magnetism, and was magnetized a second time by 6 strokes of the feeder; it now carried 26 lbs. 9 oz., or 26·5 times its own weight: it was a second time deprived of its magnetism, and after receiving 6 strokes according to Hoffer's method, it carried the same weight as at first.

Fisher says, that to impart to steel its maximum magnetic intensity, it should be heated over charcoal, or upon a hot iron plate, not, however, to such a degree as to render it soft. When the temperature has been thus raised the bar is to be stroked until it has cooled down to the temperature of the surrounding atmosphere. Theory would have led us to expect what practice confirms, that, by raising the temperature of the bar, we diminish its coercive power, and accordingly increase its susceptibility of magnetic influence. (§ 452.) The manipulation is by this means rendered unavoidably tedious.

§ 455.

Whichever of these different modes we may adopt for imparting magnetic virtue to a steel bar, the power of the magnet we employ, and the size or mass of the bar to be magnetized, will decide whether the maximum intensity will be attained or not. If the magnet have but a low power, it will excite but a feeble magnetism; but if several such magnets be arranged with their similar poles together, their power will be increased, and a more intense magnetism will be imparted by using this *compound magnet*. Both bar and horse-shoe magnets admit of being thus combined.

For instance, impart to several horse-shoe bars a feeble magnetic power, and then lay them with their similar poles one above the other. When thus combined, they will act as a powerful magnet, and may be made to impregnate still more strongly a second magnet. Detach one of the plates from the first compound magnet, and put in its place the one you last magnetized; magnetize the plate you have separated, a second time with the compound magnet; by this means its power will be greatly increased; replace it, and detach a second plate, and so on, till each has been operated on in like manner, and you will thus obtain a compound magnet of much higher power than it at first possessed. To form a compound bar-magnet the bars should be laid with their similar poles one on the other, and their ends should be connected by a piece of soft iron. A compound horse-shoe magnet consists generally of a number of plates of equal width and breadth, but of unequal lengths and intensity, the longest and most powerful plate being put in the middle. These plates are arranged in the same manner as the bars, so that the like poles may be together, their curved ends should fit exactly, and the whole may be firmly bound together by three screws, one at the head and one at each end of the magnet. The keeper may be conveniently attached to the central projecting plate. *Fig.* 147. represents a magnet of this kind. A number of bar-magnets may be so put together as to serve the purpose of either a compound bar or horse-shoe magnet; that it may act as a horse-shoe magnet, place a feeder at the end, and divide the plates by interposing a piece of wood, keeping half the number on each side; lastly, unite the lower extremity also by means of a piece of soft iron. *Fig.* 146. represents a magnet of this kind.

Fig. 146.

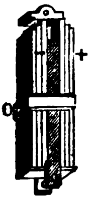
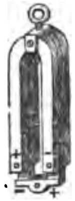


Fig. 147.



The most powerful compound magnet ever made was that constructed in the last century by Dr. Knight: it consisted of two parallelopipedons, each weighing 500 lbs., and containing 240 powerful bar-magnets, 5 feet in length. With this apparatus he is said to have reversed almost instantaneously, the poles of any natural or artificial magnet, or if the other poles were offered to have most powerfully increased their force.

§ 456.

The power of a magnet is estimated by the weight its poles are able to carry. Each pole singly is able to support a smaller weight than when they both act together by means of a keeper, for which reason horse-shoe magnets are superior to bar-magnets of similar dimensions and character. It has further been ascertained that small magnets have a much greater relative force than large ones.

When magnetism is excited in a piece of steel in the ordinary mode by friction with a magnet, it would seem that its inductive power is able to overcome the coercive power of the steel, only to a certain depth below the surface; hence we see why small pieces of steel, especially if not very hard, are able to carry greater relative weights than large magnets. Sir Isaac Newton wore in a ring a magnet weighing only 3 grains, which would lift 760 grains, *i. e.* 250 times its own weight.

Bar-magnets are seldom found capable of carrying more than their own weight, but horse-shoe magnets of similar steel will bear considerably more. Small ones of from ½ an ounce to 1 ounce in weight will carry from 30 to 40 times their own weight, while such as weigh from 1 to 2 lbs. will rarely carry more than from 10 to 15 times their weight. The author found a 1 lb. horse-shoe magnet that he impregnated by means of the feeder, able to bear 26½ times its own weight; and Fischer having adopted the like mode of magnetizing the steel, which he also carefully heated, has made magnets of from 1 to 3 lbs. weight that would carry 30 times, and others of from 4 to 6 lbs. weight that would carry 20 times their own weight. Both the form and material of the feeder seem to influence its capacity for conveying the magnetic influence. It should be of the purest iron, and perfectly free from carbon; its face should be very smooth, that the contact with the pole of the magnet may be as complete as possible; and its form should be rounded, so as to resemble a cylinder. Until lately the construction of compound magnets of extraordinary power has been rather a matter of curiosity and dilettantism than of any practical utility; but since the invention of the electro-magnetic machines, in 1833, a necessity has arisen for the construction of powerful magnets, and hence it has become of importance to ascertain the most certain and expeditious methods of imparting magnetic virtue.

M. Häcker, the philosophical instrument maker at Nürnberg, has discovered a law, the accuracy of which is confirmed by Ohm, for calculating from the weight of a horse-shoe magnet the load it will carry; or if the load be given, the weight of the magnet. This law he arrived at after performing a great number of experiments with horse-shoe magnets of all sizes, which had been magnetized to the point of saturation. (§ 452.)

Let n be the ratio of the magnet's suspensive power to its weight, W its mass or weight, then

$$\text{I.})\ a = n\sqrt[3]{W}$$

or $$\log.\ a = \log.\ n + \tfrac{1}{3}\log.\ W\ ;$$

a being a constant magnitude, which expresses the suspensive power of a magnet of some certain weight, which is assumed as the unit. M. Häcker selected 1 Bavarian loth $= \frac{1}{2}$ oz. English very nearly (the Bavarian lb. being $\frac{675}{567}$ths of the lb. avoirdupois, and the loth being the 32nd part of the lb.). From his experiments with a great number of horse-shoe magnets he found the mean value of log. $a = 1{\cdot}600$.

The above equation may be therefore converted thus: —

$$1{\cdot}600 = \log.\ n + \tfrac{1}{3}\log.\ W\ \tfrac{1}{2}\ \text{ounces};$$

Whence for the ratio of its suspensive power,

$$\log.\ n = 1{\cdot}600 - \tfrac{1}{3}\log.\ W$$

and for the weight,

$$\log.\ W = 3(1{\cdot}600 - \log.\ n).$$

Now let z be the weight it will carry, then for n in equation I.) substitute $\frac{z}{W}$, and we have

$$a = \frac{z}{\sqrt[3]{W^2}};$$

and, consequently, for its suspensive power,

$$z = a\sqrt[3]{W^2};$$

hence it is seen that the suspensive power z increases as the square of the cube root of the mass; and the first equation shows that the ratio of the suspensive power n is inversely as the cube root of the mass.

Let w W express the weights, and z Z the suspensive powers of two magnets, then they are to each other as

$$w^2 : W^2 = z^3 : Z^3,$$

or with equal values of a, the squares of the weights or masses of horse-shoe magnets are as the cubes of their suspensive forces.

To estimate exactly the intensity of magnetic forces, especially of small magnets (such as compass-needles), or to investigate the difference of such forces, we must have recourse to some other mode than that of finding the loads they would respectively carry. The most correct method is by means of Coulomb's Torsion Balance (§ 92.), or by experimenting on the oscillations made, as described in § 449.

The measurement of the magnetic intensity by the vibrations a needle performs depends on the law, that *the force by* *the exertion of which a variation needle that has been diverted from its normal position can be restored again to that position is proportional to the square of the oscillations made by the needle;* *i. e.* in other words, if this is effected by two or more forces, *their intensities are to each other as the square of the number of oscillations completed in equal times by the same needle, or they are inversely as the squares of the times of the oscillations, viz. the number of seconds required to complete the same number of oscillations.* (§ 449.)

If a common variation-needle be employed to measure the intensity of the pole of any magnet, it must be borne in mind that two forces act upon the needle to cause it to vibrate, viz. the earth's magnetism and also that of the particular pole, which is the subject under investigation. Now, to discover the influence of the latter force only, we must observe how many oscillations the needle makes in a given time under the operation of the earth's directing force alone, and deduct this number from the whole number of oscillations performed in the same time under the combined operation of this force and that of the magnet.

To perform this experiment the needle must be deflected, by means of a bar-magnet of but a small power, some 20° from the magnetic meridian; this magnet should then be withdrawn, and the needle will be acted on solely by the earth's magnetism. The time, measured by a correct seconds' watch, during which the needle performs a certain number of oscillations, will serve to measure the intensity of the force with which the earth's magnetism acts upon it.

Now, subject the needle to the action of the magnet you desire to test, by bringing one of the poles of the latter near the opposite pole of the needle; the magnet should be held in the meridian of the needle, and in the plane of the needle's vibrations. When the needle has been thus deflected, it oscillates under the influence of two magnetic forces, viz. of the earth and of the magnet. Count, as before, the number of seconds required by the needle to accomplish the same number of vibrations as before; the time will of course be less. You have now the means of measuring the sum of the two forces; subtract from it the force found by the first experiment, and the remainder will give the force with which the pole of the magnet acts on the needle.

To illustrate this still more clearly, we will suppose that to perform 20 oscillations under the influence of the terrestrial magnetism alone, a needle requires 100 half seconds, then the measure of the earth's magnetic force is

$$\frac{1}{100^2} = \frac{1}{10{,}000} = 0{\cdot}0001.$$

Next, suppose that the same needle, under the combined influence of the earth's magnetism and that of the pole of a certain magnet, performed 20 oscillations in 50 half seconds, then the sum of the two forces would be expressed thus,

$$\frac{1}{50^2}=\frac{1}{2500}=0{\cdot}0004.$$

Subtract the former measure from the latter, and we shall have the measure of the magnet's force, viz.

$$\frac{1}{2500}-\frac{1}{10{,}000}, \text{ or } 0{\cdot}0004-0{\cdot}0001=0{\cdot}0003;$$

hence in this instance, the force exerted by the pole of the magnet alone upon the needle is to that exerted by the earth as 3 : 1.

Now, if the needle be deflected in a similar manner by the pole of a second magnet held at the same distance from it, and it is found to make 20 oscillations in 30 half seconds, then the measure of the intensity of this pole's magnetism will be

$$\frac{1}{30^2}-\frac{1}{100^2}=\frac{1}{900}-\frac{1}{10{,}000}=0{\cdot}00101;$$

whence the power of this second magnet is to that of the other as 101 : 30.

This experiment may be performed as well on two, three, or more points of the same magnet as on two, three, or more separate magnets, minding, not only to keep the same distance, but also to elevate or depress correctly the vertical bar or the leg of the horse-shoe magnet, in order to test the intensity of the various points of the needle. — It is convenient in all these calculations to assume the earth's magnetism to be unity, and to represent the other magnetic forces relatively to it. Thus, in the illustrations given above, the pole of the first magnet at the particular distance would be said to exert 3 times, and the second 10·1 times the force which the earth itself does on the needle.

The following formula will furnish us with a general method of expressing the intensity of the pole of any magnet: —

$$\frac{1}{t^2}-\frac{1}{T^2}=\frac{T^2-t^2}{t^2T^2};$$

and if we put the earth's magnetism as unity,

$$\frac{T^2-t^2}{t^2},$$

T being the number of units of time (seconds, half-seconds, &c.) which the needle requires to accomplish a certain number of oscillations under the influence of terrestrial magnetism alone, and t the time in which it performs the same number of oscillations under the combined influence of the earth and the magnet under investigation.

M. Häcker, of Nürnberg, has also discovered a law by which to calculate for bar and horse-shoe magnets the time of their vibrations, and consequently their magnetic intensities. Let l and L be their lengths, w and W their weights, t and T the times of their oscillations; then the following is the proportion he found to exist: —

$$t : T = \sqrt{l}\sqrt[3]{\frac{w}{l}} : \sqrt{L}\sqrt[3]{\frac{W}{L}};$$

and as the magnetic intensities, m and M, are indirectly, as the squares of their times of oscillation, it follows,

$$\begin{aligned} m : M &= \frac{1}{t^2} : \frac{1}{T^2} \\ &= \frac{1}{\left(\sqrt{l}\sqrt[3]{\frac{w}{l}}\right)^2} : \frac{1}{\left(\sqrt{L}\sqrt[3]{\frac{W}{L}}\right)^2} \\ &= \sqrt[3]{L\,W^2} : \sqrt[3]{l\,w^2}; \end{aligned}$$

i.e. the intensities of bar-magnets are proportional to the cube root of the product squared of their length into their width.

By similar experiments on their oscillations, Coulomb had deduced his law, § 440., that the attractive forces decrease with the increase of the distance. Thus, by this mode of investigation, he found that a needle, which under the influence of terrestial magnetism alone performed 15 oscillations in 1 minute, made 24 such oscillations in the same time, when he held the opposite pole of a magnet in the plane of its magnetic meridian at a distance of 8 inches; and 41 oscillations when the distance was only 4 inches. In this case, the distances were as 2 to 1, and the attractive forces of the magnet as $24^2 - 15^2 : 41^2 - 15^2 = 351 : 1456$, or nearly as 1 to 4.

If the *torsion balance* (*fig.* 36. Vol. I. p. 95., the theory of which has already been explained in § 92.), be used as a magnetometer, to verify the preceding law, then for the bar *ld* substitute a magnetized needle, which is to come to a state of a rest in the magnetic meridian, without the wire being thereby twisted. Now, bring this needle in the plane of its oscillations, turning it towards the similar pole of a magnet, and repulsion will, of course, ensue. We will suppose the angle of repulsion to be 24°, and if we give to it an opposite torsion of 3 × 360 = 1080°, the deflection would be only 17°. But by the preceding experiments we already know that if the magnet of a torsion balance be turned 35°, it will be deflected about 1° from its polar position; if its deflexion be 24°, then the torsion it has suffered must be 24 × 35 = 840°; if it be 17°, 17 × 35 = 595. Hence the deflecting power which causes an angle of repulsion of 24° is to that which causes an angle of repulsion of 17°, as 24 + 840 : 17 + 1080 + 595 = 864 : 1692, or nearly as 1 : 2, whilst the squares of the deflections will be as $24^2 : 17^2 = 576 : 289$, or nearly as 2 : 1.

By means of this apparatus, the intensities of different magnets may be proved. For this purpose, deflect the needle of the torsion balance by the pole of the magnet under investigation, some certain distance from its normal position. By turning the wire in the opposite direction, the needle can be carried back to any angle of deflection whatever. With the pole of another magnet, or with some other part of the same magnet, proceed as before, taking care that the force shall act from the same point in each case, and that the needle is brought back to the same point. Then the intensities of the two magnetic forces are as the angles of torsion of the wire. For instance, if the needle must be turned back to 90°, in order that the magnet *m* should deflect it 10°, and if it had to be turned 290° for another magnet M to deflect it as much, then the intensities of these two magnets would be as 90 + 10 = 100 to 290 + 10 = 300, or as 1 : 3.

§ 457.

We have already (§ 438.) stated that magnetism may be induced in bodies susceptible of this influence, by merely bringing them within the atmosphere of either a natural or an artificial magnet: the part nearest to the magnet acquiring an opposite polarity to that of the pole, within whose magnetic circle it is placed.

This mode of exciting magnetism is far less effective than either contact or friction. It is more powerful in its influence on soft iron than on steel, for reasons already assigned (§ 452.); but in both, its effects are but temporary. — The experiments described in § 439. are a proof of this.

Terrestrial magnetism especially operates in this manner upon all bodies susceptible of this influence, as is seen in the magnetic properties acquired by bars of iron or steel placed in a vertical position, or better still, in the direction in which the directing force of the earth's magnetism acts. (§ 447.) Bodies so placed in the northern hemisphere have their upper extremities converted into south poles, and their lower ends into north poles. As far as polarity is concerned, these circumstances are reversed in the other hemisphere. — As a proof, see the experiment given in § 446.

§ 458.

Soft iron becomes magnetized by a variety of *mechanical operations*, which probably have the effect of disturbing the magnetic equilibrium of its constituent particles. Thus, an iron bar acquires magnetic properties by striking, filing, twisting, cooling rapidly, &c.; and it is a well known fact that iron and steel tools, such as gimlets, nail-passers, files, and the like, after having been some time in use, become so far magnetized as to take up iron-filings: an iron bar will be most quickly magnetized if subjected to such treatment while held in the position of the dipping-needle.

> *First Expt.* Hold an iron bar, about two feet long, in the position of the dipping-needle, and strike its upper end smartly with a hammer; its lower end will immediately become a tolerably powerful north pole, and the upper a south pole. The magnetism thus imparted will be still more powerful if the lower end of the bar be placed on a mass of iron when struck.
>
> *Second Expt.* If a bar of iron be made red-hot, by which means its coercive power will be greatly lessened (§ 452.), and then plunged into a vessel of cold water (observing, at the same time, to hold it in the position of the dipping-needle), it will be found to be polarised, and to have acquired a considerable degree of magnetic force.

From these phenomena, it appears plain that these bodies are in the main rendered magnetic by induction from the earth, and that the mechanical treatment to which they are subjected merely disposes them more readily to allow of the separation of the magnetic forces.

§ 459.

Some philosophers are of opinion that *magnetic virtue is imparted by means of the sun's rays.* The results to which the experiments they performed for ascertaining this point have conducted them are as follow: — Small pieces of iron, or soft steel wire, became magnetic if they had one end polished, and if this end was exposed for some time to the action of the white light of the sun; if the needles were subjected to the violet rays of the solar spectrum, the effect was produced still more speedily. In either case, the magnetism was permanent in its character, and the illuminated end of the wire was a north pole. The magnetism thus induced is extremely feeble, and the experiment has been successfully conducted only during the longest days of summer, and under favourable circumstances as regarded the state of the weather. These experiments have been repeated by other philosophers; but the results have been doubtful, and we are not warranted in stating positively that the sun does possess any magnetic influence.

Morichini, in 1812, was the first who announced that he had magnetized needles by exposing them for some time to the action of the violet rays of the solar spectrum, which he concentrated by means of a lens, and threw down on the needles. His colleague Barlocci believed that he accelerated the process and rendered the magnetism more intense, by moving the image of the violet rays from the middle of the needle towards the ends, which he placed north and south, moving it pretty much as we do a magnet when using it to impregnate a steel bar. Mrs. Somerville, in 1825, repeated Morichini's experiments with certain modifications; such as covering one half of the needle to be magnetized with paper, and exposing the naked half to the action of the violet rays. After some time she found the needle was rendered magnetic, and the end acted on by the light was a north pole. Professor Baumgartner, in 1826, found that needles from one-third to one-fourth of a line in thickness, if they were polished only at one end, and were either rough or stained with some dark colour in the other part, were rendered magnetic by exposure to the sun's rays, and that the polished end was invariably a north pole. Lastly, Zantedeschi, in 1829, verified the preceding experiments, and found that the needles must not be more than one-fourth of a line thick, and that they must not be too hard if the experiment is to be successful; and lastly, that the most favourable temperature for this purpose is from 77° to 91° Fahr.

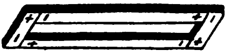
Shortly after Morichini's announcement, Configliarchi called in question the accuracy of his statements; and Reiss and Moser are of opinion that the sun does not possess the magnetic properties some have been disposed to attribute to his rays, as in a set of experiments they performed at Berlin in 1829, they subjected the half of a number of needles two hundred times to a focus of violet light, and subsequently tested the duration of their oscillations without finding the least difference to have been caused which could lead them to believe they had been rendered magnetic.

§ 460.

Lastly, little more than twenty years ago it was discovered that one of the most powerful means for exciting magnetism was electricity; and thus, indirectly indeed, heat was an exciting cause. Since, however, this does not admit of being explained without some acquaintance with the phenomena of electricity, all further remarks on this subject must be delayed till we come to the section on electro-magnetism.

§ 461.

Fig. 148.



The retention and increase of the magnetic influence in magnets depends on the antagonist magnetism being collected at the poles being secured from escaping. In bar-magnets this is accomplished by laying them with their unlike poles together; or, better still, by placing a piece of soft iron between each pair of such poles, as is shown in *fig.* 148. A keeper secured in this position, by induction maintains the opposite polarity at its points of contact with the poles of the magnet; thus, four pairs of antagonist poles being in contact strengthen each other. The keeper, placed against the poles of a horse-shoe magnet, acts in a similar manner.

The virtue of a magnet may be further increased by continually adding to the load it carries.

Lastly, it is advantageous to give to a magnet the very position it would assume, had it free motion, as the earth's magnetism will contribute both to maintain and increase its power when in the magnetic meridian.

§ 462.

The magnetic properties of a magnet are impaired by any of those operations, which tend to diminish its coercive power, or which affect the regularity of its surface, but most of all by the similar poles of two magnets being allowed to act on each other.

One chief mode of weakening the coercive power is (§ 452.) by heating the magnet, which, if raised to a red-heat, loses all its magnetic properties.—Rust also diminishes its virtue in exactly the same degree as it roughens the face of a magnet. But the readiest way to demagnetize a magnet is to draw another magnet along its surface in a direction the opposite to that you would adopt in order to impart magnetic virtue to the bar. By this process a magnet may be deprived of the greater part, or even of the whole, of its magnetism. The following experiment will prove this:—

Expt. Lay the magnet N, *fig.* 142., which you wish to demagnetize, in such a manner on the magnet M that the dissimilar poles may be together, and then draw it down in the direction of the arrows. After this has been done a few times, the virtue of N will have either almost or entirely disappeared. Similar results follow, if any of the other modes of manipulation be adopted, taking care to reverse the touch, so that it shall be exactly opposite to that used when you impregnate a bar.

By continuing the process a sufficient time, you will reverse the poles of a magnet.

Magnets also lose this power if they lie for any length of time without their poles being connected by means of a keeper, or if they are struck or jarred, but especially if the keeper is repeatedly and quickly separated from them.

Every magnet which has been impregnated with a keeper attached to it, has a maximum magnetic intensity, so long as the latter is connected with it: indeed, it is in a state in which it may be said to be overcharged, (§ 452.) Its power to support a weight is impaired most sensibly after the first removal of the keeper; its loss of power is less on the second and every subsequent removal, until after a few times the separation of the keeper ceases perceptibly to affect the magnet when it has reached its natural point of saturation. The power of a magnet is diminished most quickly by forcibly and quickly removing the keeper. To secure the efficiency of a magnet from being needlessly impaired, care should be taken to remove the keeper as seldom as possible; and when, for the sake of performing an experiment, the removal is necessary, draw it off sideways from the poles.

§ 463.

In the preceding paragraphs, the different methods have been described by which the magnetic equilibrium may be disturbed, and the polar forces excited in iron and steel, which are *par excellence* magnetizable substances. Several distinguished philosophers have recently found, by experiments on their vibrations (such as are described, § 456.), that other bodies, generally considered non-magnetizable, such as the metals which have a regular structure, wood, glass, shell-lac, &c., acquire a temporary magnetism when acted on by a powerful magnet. They are further of opinion, that slight traces of magnetism are discoverable in bodies of the most varied character, if firmly connected with the earth's surface; the impregnation of these bodies they attribute to the influence of terrestrial magnetism.

From all these experiments and observations they have drawn the conclusion that, probably, all bodies on the surface of our earth, at least all solid bodies, may become temporarily magnetic in a certain degree, and that every portion of the globe, and every body on it, shares in the general conduction of the terrestrial magnetism. (§ 451.)

The analogous phenomena of electro-magnetism and magneto-electricity, treated of in the fourth and fifth sections of this work, confirm this opinion.

Coulomb, in 1802, first announced the discovery, that magnets exerted an influence on all kinds of bodies, whether in a state of rest or oscillation, from which he inferred the presence of magnetism in the latter. Small bars of various substances, which he suspended by a piece of thread so as to move freely when placed between the dissimilar poles of two powerful magnets, arranged themselves in the direction of these poles; and when deflected from this position they began a series of oscillations, which they performed with different velocities until they again returned to their state of repose. Biot, Seebeck, and Becquerel subsequently repeated Coulomb's experiments, to test the presence of iron in other bodies.

Hansteen is of opinion, that all bodies whatever on the the earth's surface have a certain degree of magnetic polarity: he thought he had observed, that a needle held near to the ground on the north side of a tree, post, column, &c., made a greater number of vibrations in a given time than when held on the south side; but that the same needle, when presented to the upper end of the object, vibrated more rapidly on the south side than on the north side; whence he inferred that all bodies had a low degree of polarity imparted to them by the earth's magnetism; that their lower end in the ground was a north pole, and their upper end a south pole.

END OF THE SECOND VOLUME.

LONDON:
Printed by A. SPOTTISWOODE,
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